Late Saalian and Eemian palaeoenvironmental history of the Bol'shoy Lyakhovsky Island (Laptev Sea region, Arctic Siberia)

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Palaeoenvironmental records from permafrost sequences complemented by infrared stimulated luminescence (IRSL) and ^{230}Th/U dates from Bol'shoy Lyakhovsky Island (73°20′N, 141°30′E) document the environmental history in the region for at least the past 200 ka. Pollen spectra and insect fauna indicate that relatively wet grass-sedge tundra habitats dominated during an interstadial *c.* 200–170 ka BP. Summers were rather warm and wet, while stable isotopes reflect severe winter conditions. The pollen spectra reflect sparser grass-sedge vegetation during a Taz (Late Saalian) stage, *c.* 170–130 ka BP, with environmental conditions much more severe compared with the previous interstadial. Open Poaceae and *Artemisia* plant associations dominated vegetation at the beginning of the Kazantsevo (Eemian) *c.* 130 ka BP. Some shrubs (*Alnus fruticosa, Salix, Betula nana*) grew in more protected and wetter places as well. The climate was relatively warm during this time, resulting in the melting of Saalian ice wedges. Later, during the interglacial optimum, shrub tundra with *Alnus fruticosa* and *Betula nana s.l.* dominated vegetation. Climate was relatively wet and warm. Quantitative pollen-based climate reconstruction suggests that mean July temperatures were 4–5°C higher than the present during the optimum of the Eemian, while late Eemian records indicate significant climate deterioration.

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Palaeoenvironmental, especially palynological, studies have already been conducted on permafrost sections in the Northern Yakutia (Rybakova 1962; Giterman 1976–1977; Lozhkin 1977; Sher *et al.* 1977; Kaplina 1979; Kaplina *et al.* 1978, 1980; Kaplina & Giterman 1983; Tomirdiaro 1980; Barkova 1982, 1990; Rybakova & Kolesnikov 1983; Rybakova & Pirumova 1986; Alekseev 1989, 1997; Makeyev *et al.* 1989, 2003; Igarashi *et al.* 1995; Andreev *et al.* 2001, 2002a), but only a few of them are relatively well dated and at a high resolution, making the chronological correlation of the reconstructed environmental fluctuations difficult.

In 1998–2001 the permafrost sequences on the Bykovsky Peninsula (Mamontovy Khayata site) and north of the Chekanovsky Ridge (Buor-Khaya site) were studied within the scope of the research project 'Palaeoclimate signals in ice-rich permafrost' established by the German–Russian science cooperation 'Laptev Sea System'. These multidisciplinary studies have greatly improved the knowledge of the Late Quaternary environmental history of the region (e.g. Andreev *et al.* 2002a; Meyer *et al.* 2002a; Schwamborn *et al.* 2002; Krbetschek *et al.* 2002; Schirrmeister *et al.* 2002a, in press; Kienast 2002; Kuzmina 2002; Bobrov *et al.* 2004). The Quaternary deposits of the southern coast of Bol'shoy Lyakhovsky Island were first noted by Bunge (1887) and Toll (1897). First detailed studies were carried out much later by Romanovskii (1958a–c), according to whom the deposits consist of lagoon and flood-plain sediments. In contrast, Japanese researchers propose that the Ice Complex deposits were formed in a large swampy marshland on the dried Pleistocene Laptev Sea shelf (Nagaoka 1994; Nagaoka *et al.* 1995), whereas Kunitsky (1998) considers them to be formations connected with perennial snow patches on cryoplanation terraces.

Discussions about the age of the studied deposits are also controversial. According to Romanovskii (1958a, b) their age varies from the Middle/Late Pleistocene (for the oldest deposits) to the Holocene, whereas Arkhangelov *et al.* (1996), based on TL dates (980 ± 250 ka and 950 ± 250 ka) and palaeomagnetic analyses, pro-

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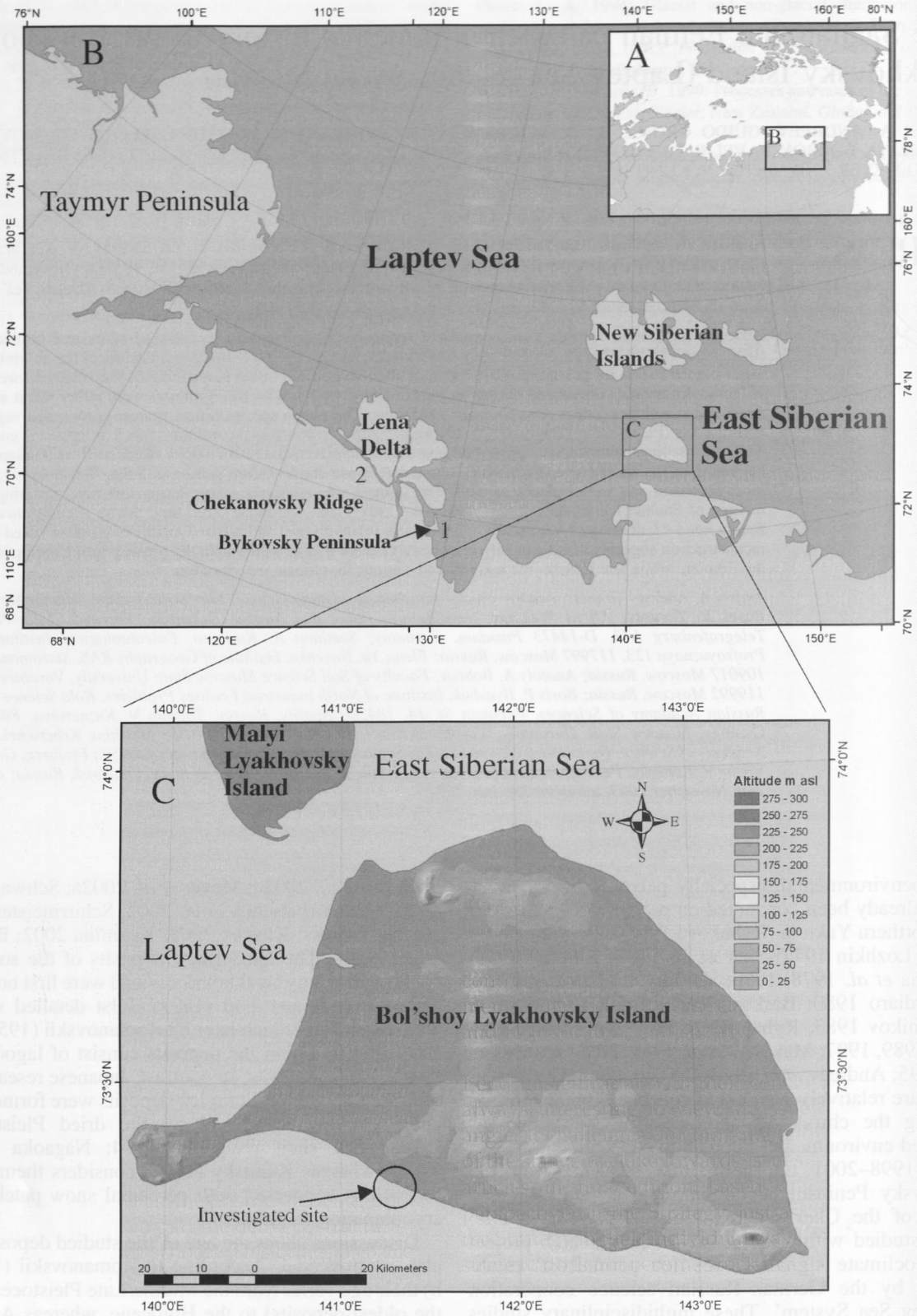

Fig. 1. A. Map of the Arctic. B. Map of the Laptev Sea – Bol'shoy Lyakhovsky Island region. 1 – Mamontovy Khayata site, 2 – Buor-Khaya site. C. Study area on Bol'shoy Lyakhovsky Island.

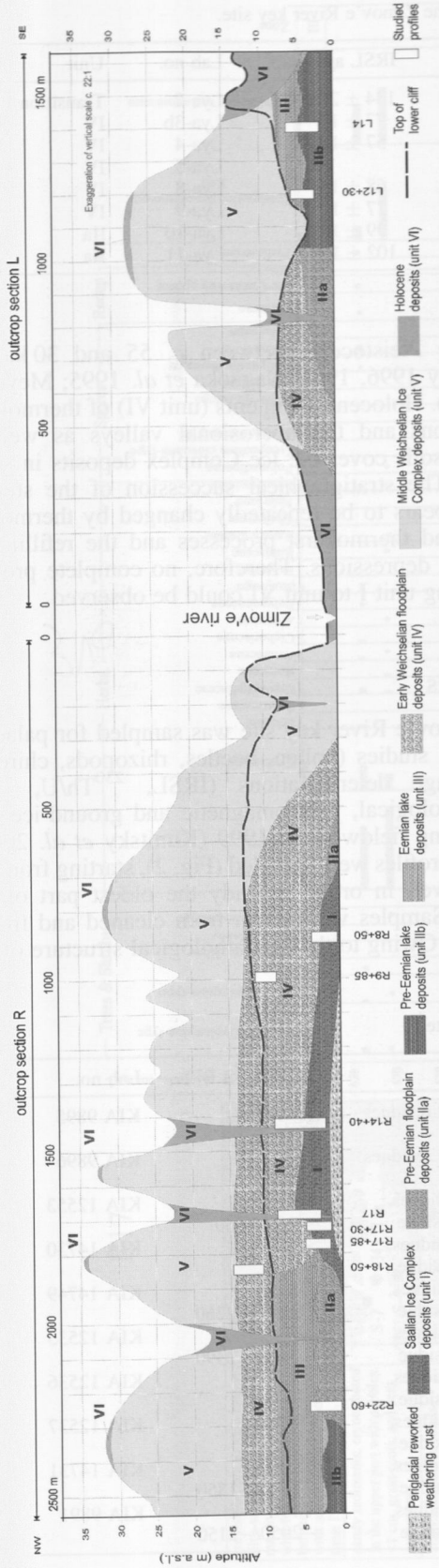

Fig. 2. The coastal section around Zimov'e river mouth and locations of studied profiles.

posed a late Pliocene/early Pleistocene age for the lowest deposits.

Recent studies of permafrost sequences from a key site situated on the southern coast of Bol'shoy Lyakhovsky Island at the mouth of Zimov'e River (Fig. 1) were also carried out within the scope of the project 'Palaeoclimate signals in ice-rich permafrost'. New palaeoenvironmental records dated by ^{230}Th/U, IRSL and ^{14}C methods document the environmental oscillations in the region from at least *c.* 200 ka until the present. This paper presents new palaeoenvironmental reconstructions since an interstadial during the Taz (Late Saalian) time, prior to 200 ^{230}Th/U ka ago up to the Zyryanian (Early Weichselian) stage *c.* 60–70 ka ago.

Study area

Large areas of the Bol'shoy Lyakhovsky Island are covered by ice-rich permafrost deposits. A key site located on the southern coast of Bol'shoy Lyakhovsky Island on the Dmitri Laptev Strait (73°20′N, 141°30′E, Fig. 1) was studied in summer 1999. This site consists of coastal and thermoerosion cliffs up to 40 m high extending for about 2.5 km to the east and about 3.5 km to the west from the Zimov'e River mouth (Fig. 2).

The modern climate of the area is characterized by long (8 months), severe winters with January temperatures of −31 to −32°C and short, cold summers with July temperatures around 4°C and about 200 mm annual precipitation (Atlas Arktiki 1985). Soils in the area are mainly tundra-gley and peaty-gley (histosols and inceptisols) with an active-layer thickness of about 30–40 cm (Atlas Arktiki 1985). Permafrost has a thickness of 500–600 m (Grigoriev *et al.* 1996). The area belongs to the northern tundra zone (Atlas Arktiki 1985). Moss-grass–low-shrub tundra dominates the vegetation, with vascular plant species such as *Salix pulchra, Cassiope tetragona, Dryas punctata, Oxyria digyna, Alopecurus alpinus, Poa arctica, Carex ensifolia, C. rotundifolia* and *Eriophorum medium*, mosses such as *Aulacomnium turgidum, Hylocomium alaskanum, Drepanocladus iniciatus* and *Calliergon sarmentosum* and lichens such as *Alectoria ochroleuca, Cetraria cuculliata* and *C. hiascus*.

The lowest (oldest) frozen soft rocks are periglacially reworked remains of a yellowish to greenish coloured Palaeogene weathering crust exposed at sea level (Kunitsky *et al.* 2000). The overlaying unit (unit I) contains ice-rich silty and silty-sandy deposits with pebbles, peat inclusions and peat horizons. Ice belts, lens-like reticulated interlayers and wide ice wedges with symmetric shoulders are indicative of syngenetic permafrost conditions. Unit I is suggested to be the deposit of an old Ice Complex, similar to the Late Pleistocene (Weichselian) Ice Complex formation that

Table 1. Infrared stimulated luminescence (IRSL) dates from the lower units of the Zimov'e River key site.

Sample ID (altitude a.s.l.)	Annual dose rate (Gy/ka)	Palaeodose (Gy)	IRSL age (ka)	Lab no.	Unit
R17, 500 cm	2.63 ± 0.43	352 ± 7.2	134 ± 22	Lya-2	Transition I to IV
R17, 750 cm	3.66 ± 0.65	283.2 ± 14.1	77 ± 14	Lya-3b	IV
R18+50-B11, 1290 cm	3.70 ± 0.64	210.3 ± 12.3	57 ± 10	Lya-4	IV
R18+50-B13, 1470 cm	Not datable			Lya-5	IV
R9+85, 880 cm	3.36 ± 0.59	227.5 ± 24	68 ± 14	Lya-8	IV
R9+85, 1020 cm	4.03 ± 0.62	310.4 ± 9.1	77 ± 12	Lya-9	IV
R22+60, 100 cm	4.06 ± 0.61	402 ± 10.3	99 ± 15	Lya-10	IIa
R22+60, 200 cm	4.14 ± 0.60	422.9 ± 20.8	102 ± 16	Lya-11	IIa

is widely distributed in northeastern Siberia. The next unit (unit II) mostly forms the lower part of the coastal cliff up to about 6 m a.s.l. Two different facies subunits were observed. Unit IIa consists of well-sorted, homogenous loess-like fine-grained silty to sandy, relatively ice-poor sediments with massive cryostructure containing numerous vertically orientated roots, small ice and sand-ice wedges. Unit IIb consists of laminated, bluish-grey sediments containing numerous shells of the freshwater molluscs (*Pisidium* sp., *Sphaerium corneum, Valvata piscinalis, Lymnaea* cf. *peregra*) and freshwater ostracods. Unit IIb is sinuously deformed (amplitude 2–3 m, length 10–20 m) and sporadically covered by a horizon of ice-wedge casts with laminated subaquatic deposits (unit III). Younger loess-like deposits, very similar to unit IIa, exposed between 3 and 15 m a.s.l., are considered as unit IV. They contain more ice as ice belts and larger ice wedges. The subsequent Ice Complex deposits (unit V) form steep walls up to 25 m high. This unit is composed of wide (up to 6 m) and long (up to 25 m) ice wedges and sandy sediments with numerous peat lenses and palaeosol horizons, especially in the upper part. Unit V was formed during the Late Pleistocene, between *c.* 55 and 30 ka BP (Kunitsky 1996, 1998; Nagaoka *et al.* 1995; Meyer *et al.* 2002). Holocene sediments (unit VI) of thermokarst depressions and thermoerosional valleys as well as modern soils cover the Ice Complex deposits in some places. The stratigraphical succession of the studied units appears to be repeatedly changed by thermoerosional and thermokarst processes and the refilling of temporal depressions. Therefore, no complete profiles containing unit I to unit VI could be observed.

Methods

The Zimov'e River key site was sampled for palaeoecological studies (pollen, beetles, rhizopods, chironomids), age determinations (IRSL, ^{230}Th/U, ^{14}C), sedimentological, palaeomagnetic and ground-ice studies during fieldwork in 1999 (Kunitsky *et al.* 2000). Several profiles were sampled (Fig. 2), starting from the beach level, in order to study the oldest part of the section. Samples were taken from cleaned and frozen deposits. Owing to the cryolithological structure of the

Table 2. AMS radiocarbon dates from the lower units of the Zimov'e River key site.

Sample ID (altitude a.s.l.)	Dated material		^{14}C age (ka BP)	Lab no.	Unit
LYA-L14 S3, 420 cm	Roots and twigs	Leached residues	>50420	KIA 9895	IIb
LYA-L14 S4, 540 cm	Small roots and twigs	Leached residues	>50880	KIA 9896	III
LYA-R17 S8, 670 cm	Plant detritus	Plant residues, alkali residue	36510 + 960/−860	KIA 12553	IV
LYA-R8+50 S12, 90 cm	Moss	Plant residues, alkali residue	>53250	KIA 14730	I
LYA-R8+50 S37, 300 cm	Plant remains	Plant residues, alkali residue	49810 + 3150/−2260	KIA 14749	IV
LYA-R18+50B11 S2, 1270 cm	Wood and plant remains	Plant residues alkali residue	44000 + 3430/−2390	KIA 12535	IV
LYA-R18+50Bj13 S6, 1375 cm	Plant remains	Plant residues, alkali residue	>54050	KIA 12536	IV
LYA-R18+50Bj13 S8, 1350 cm	Plant remains	Plant residues, alkali residue	>44160	KIA 12537	IV
LYA-R9+85 S4, 900 cm	Moss	Plant residues, alkali residue	49200 + 2400/−1850	KIA 14731	IV
LYA-R14+40 S8, 660 cm	Roots, wood, plant remains	Plant residues, alkali residue	50110 + 2950/−2150	KIA 9891	IV

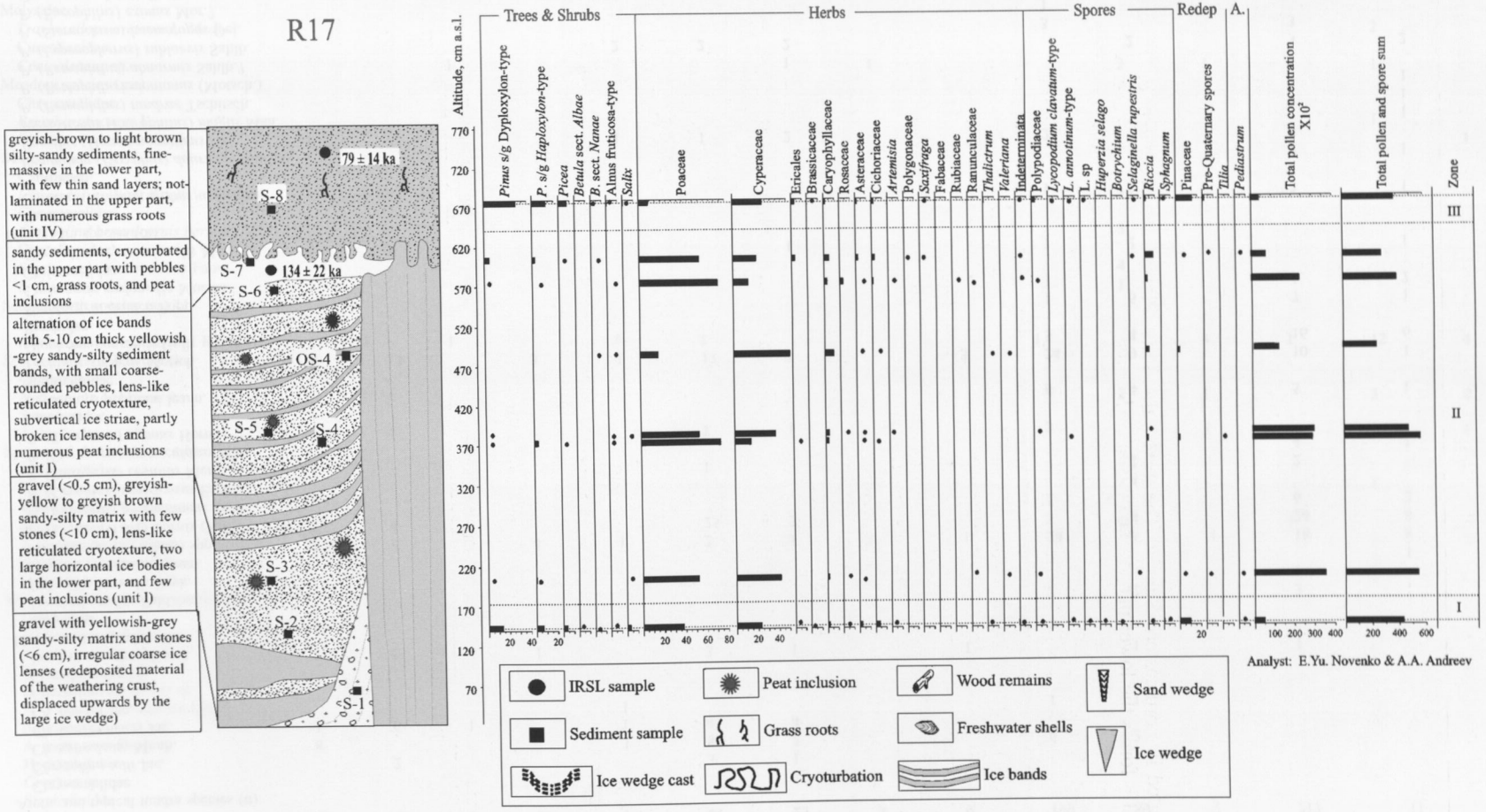

Fig. 3. Cryolithological structure and pollen percentage diagram of section R17.

Table 3. List of beetle taxa found in Zimov'e River key site (for explanations of abbreviations of ecological groups, see 1st column).

Sample ID (altitude, cm a.s.l.)	R17-R4, 420	R17-B2, 450	R17-B1,520	R17+30-R3, 320	R17+30-R2,360	R14+30-R5,400	R14+30-R6,440	R22-B13,120v	R22-B14, 240	R22-B15, 250	R22-B16,400	12+30-B18, 350	L12+30-B17, 400	L12+30-B19, 700
Dominating ecological groups	tt/mt	tt/mt/dt	tt/dt	tt/mt/dt	tt/mt/dt	tt/mt/dt	tt/mt/dt	dt/aq	mt/dt	mt/dt/ss/st	mt/dt/aq	na	mt/dt/na/aq	mt/dt/na/ss
No. of species (*n*)	*n*	%	*n*	*n*	*n*	%	*n*	*n*	*n*	%	%	*n*	%	%
or %	9/9	26/52/12	1/1	4/7/8	5/2/9	22/57/16	8/11/5	1/1	4/3	36/30/15/6	46/21/9	2	45/19/10/8	45/27/7/6
Total sum (*n*)	21	42	2	26	19	81	25	3	9	199	89	7	217	71
Arctic and typical tundra species (tt)														
Chrysomelidae														
Chrysolina tolli Jac.		2				3	1							
Ch. subsulcata Mnnh.	8				3	8	2			6	2			
Ch. wollosowiczi Jac.	1	6	1		1	4	4							
Ch. bungei Jac.					1					1	1			
Chrysolina sp.				3										
Curculionidae														
Isochnus arcticus Korot.		3		1		3	1		1		1		1	
Mesic tundra species (mt)														
Carabidae														
Diacheila polita Fald.										2	2		3	
Pelophila borealis Payk.													1	
Blethisa catenaria Brown.														1
Pterostichus (Cryobius) spp.	3	3		4	1	2	1		1	24	6	1	18	8
P. (Cryobius) brevicornis (Kirby)	3	4				25	5			3	4		24	8
P. (Cryobius) pinguedineus Esch.										5			6	2
P. (Cryobius) ventricosus Esch.											4			
P. (Steroperis) costatus Men.	1					1					1		2	
P. (Steroperis) vermiculosus Men.													4	1
P. (Steroperis) agonus Horn.		1				1	1			3				
Leiodidae														
Cryocatops poppiusi Jeann.										4	4		5	1
Staphylinidae														
Tachinus arcticus Motsch.	1	13		3	1	17	3		3	24	9		10	1
Olophrum consimile Gyll.										3	4		16	6
Byrrhidae														
Simplocaria arctica Popp.										1	5		7	1
Curimopsis cyclopedia Muenst.										1			1	2
Chrisomelidae														
Chrysolina septentrionalis Men.	1	1					1			1	2			1
Dry tundra species (dt)														
Carabidae														
Carabus (Morphocarabus) odoratus Motsch.										1	1		3	1
Bembidion (Peryphus) dauricum Motsch.													2	1
Poecilus (Derus) nearcticus Lth.	1				1	1	2			2			3	
Pterostichus (Petrophilus) magus Man.														1
P. (Petrophilus) tundrae Tschitsch.														1
P. (Petrophilus) montanus (Motsch.)														1
P. (Petrophilus) abnormis Sahlb.?							1							
P. (Lyperopherus) sublaevis Sahlb.					2	2	2				2		3	2
P. (Stereocerus) haematopus Dej.										3			3	
P. (Europhilus) eximus Mor.?										1				
Curtonotus alpinus Payk.		5	1	6	2	10		1	2	45	11	1	23	8
Amara (s.s.) interstitialis Dej.									1	1				1
Trichocellus mannerheimi Sahlb.										2	2		1	
Apionidae														
Metatrichapion tschernovi T.-M.											1			1
Curculionidae														

| | | |

Table 3. continued.

Sample ID (altitude, cm a.s.l.)	R17-R4, 420	R17-B2, 450	R17-B1,520	R17+30-R3, 320	R17+30-R2,360	R14+30-R5,400	R14+30-R6,440	R22-B13,120v	R22-B14, 240	R22-B15, 250	R22-B16,400	12+30-B18, 350	L12+30-B17, 400	L12+30-B19, 700
Notaris bimaculatus F.										1			1	
Heteroptera, Saldidae														
Salda sp.											1			
Aquatic species (aq)														
Dytiscidae														
Agabus sp.						1		1			1		7	2
Hydroporus sp.	1			1							2		6	
Colymbetes sp.										2	1		2	1
Gyrinidae														
Gyrinus sp.													1	
Hydrophilidae														
Helophorus (s.s.) splendidus Sahlb.		1				1				2	3		1	
H. (Gephelophorus) sibiricus Motsch.											1			
Hydrobius fuscipes F.													1	1
Other species (oth)														
Leiodidae														
Agathidium sp.													2	
Staphylinidae														
Deliphrum sp.								1		1	1	1	3	
Tachyporus sp.										1				
Lathrobium sp.										1			2	
Quedius sp.													1	1
Staphylininae indeterminata											1		1	
Curculionidae indeterminata										1				
Lathridiidae indeterminata										2	1		1	
Coccinellidae indeterminata										1				
Coleoptera indeterminata													1	

deposits and the geomorphologic situation, it was not possible to sample one continuous section; therefore samples were taken from thermokarst mounds (baydzharakhs) in which deposits remain *in situ* after melting of the surrounding ice wedges.

A standard HF technique was used for pollen preparation (Berglund & Ralska-Jasiewiczowa 1986). At least 200 pollen grains were counted in every sample. The relative frequencies of pollen taxa were calculated from the sum of the terrestrial pollen taxa. Spore percentages are based on the sum of pollen and spores. The relative abundances of reworked taxa (Tertiary spores and redeposited Quaternary pollen) are based on the sum of pollen and redeposited taxa, and the percentages of algae are based on the sum of pollen and algae. The Tilia/TiliaGraph software (Grimm 1991) was used for the calculation of percentages and for drawing the diagrams. Diagrams were zoned by visual inspection.

Samples for beetle remains were sieved through a 0.5 mm (samples marked with B) and 1 mm (samples marked with R) mesh. Originally, the R-marked samples were intended to be used for rodent analyses, but only a few rodent remains were found. The sample size varied from 40 kg (for detritus-rich samples) to 200 kg (for samples containing few plant and insect remains). Later, the insect remains were picked manually under a binocular microscope.

Samples for chironomid analysis were mixed with water, but were not sieved through a mesh. The analysis followed methods outlined in Walker (2001). Taxonomic identification was carried out followed Wiederholm (1983) and Makarchenko & Makarchenko (1999).

Samples for testate amoebae analysis were sieved through a 0.5 mm mesh and testate amoebae shells were concentrated with a centrifuge. A drop of suspension was placed on the slide, and then glycerol was added. Normally, five subsamples were examined at ×200–400 magnification with a light microscope.

Eight samples from selected profiles were dated by the infrared stimulated luminescence (IRSL) technique (Table 1). IRSL has already been successfully applied for dating Late Quaternary deposits in the Lena Delta (Krbetschek *et al.* 2002; Schirrmeister *et al.* in press). The additive dose protocol was used for calculation of the palaeodose (Aitken 1998). The samples, each divided into 48 aliquots, were stepwise radiated artificially with a Sr/Y β-irradiator. After irradiation the samples were heated at 140°C for 48 h to remove the unstable components of the luminescence signal. The IRSL measurements were carried out using a Risø TL/OSL DA12 automated luminescence reader (Risø National Laboratory, Denmark). Luminescence stimulation was performed at a wavelength of 880 nm with an optical power of 40 mW cm^{-2}. The IRSL of the 410 nm feldspar emission-peak (Krbetschek *et al.* 1997) was measured using a 410/10 nm FWHD interference bandpass optical filter (Andover Corp.). For each sample, natural normalization (0.1 s short-shine measurements of natural signal), final measurement (100 s shine-down measurements) and fading tests (0.1 s short-shine measurements repeated on the same aliquots after 2–3 months' storage) were conducted. A saturation exponential luminescence versus additive-dose characteristics was fitted using the ANALYST software (Duller 2001). The measurements were normalized by the natural short shine signal and a late-light subtraction was applied. The plateau-test (palaeodose versus stimulation time) was applied to obtain information about the bleaching level at the time of deposition (Aitken 1998). Generally, the luminescence signals were close to saturation. All samples show good plateaus with constant palaeodoses versus increasing stimulation time. The growth-curve fit was repeated for the final palaeodose and error determination using the integral values of the plateau. The dose-rate determination was performed by low-level high-resolution gamma spectrometry. For the dose-rate calculation, the natural radionuclides, cosmic radiation values and water/ice contents were used. The software of Grün (1992) based on procedures from Aitken (1985) was used to calculate ages and error bars.

Another dating technique used for peaty sediments at this study site is the ^{230}Th/U method. The results obtained were published by Schirrmeister *et al.* (2002b).

As the general stratigraphy of the subsampled profiles was not clear in the field and previously published age determinations were controversial, some selected plant remains from the investigated profiles were also collected for AMS radiocarbon dating at the Leibniz Laboratory, Kiel (Table 2). The obtained ages are close to or beyond the limit of ^{14}C method and not comparable with the ^{230}Th/U and IRSL ages, nor with geologically expected ages according to the stratigraphical positions of the samples in the outcrops. It is possible that some of the AMS-dated organic matter was removed by cryoturbation or by thermoerosional processes. Therefore, no ^{14}C dates have been used for age estimation of the investigated deposits, which were considered to be pre-Eemian and Eemian.

A total of 10 oriented samples (each in 6 subsamples) from 3 profiles of units I and II were collected for palaeomagnetic analyses. For the sampling, a 45-mm sheet-steel cube with flat surfaces has been used. The samples were stored in special 24 × 24 mm cardboard boxes. The palaeomagnetic analyses were carried out at the Laboratory of Main Geomagnetic Field and Magnetic Petrology, Institute of Physics of the Earth, Russian Academy of Sciences.

The best modern analogue (BMA) method (Guiot 1990) was used to reconstruct climate characteristics from the pollen spectra attributed to the Eemian. The method has recently been applied to lateglacial and Holocene pollen records from the Russian Arctic (Andreev *et al.* 2003a, b, 2004). The accuracy of the BMA method in comparison with other pollen-based

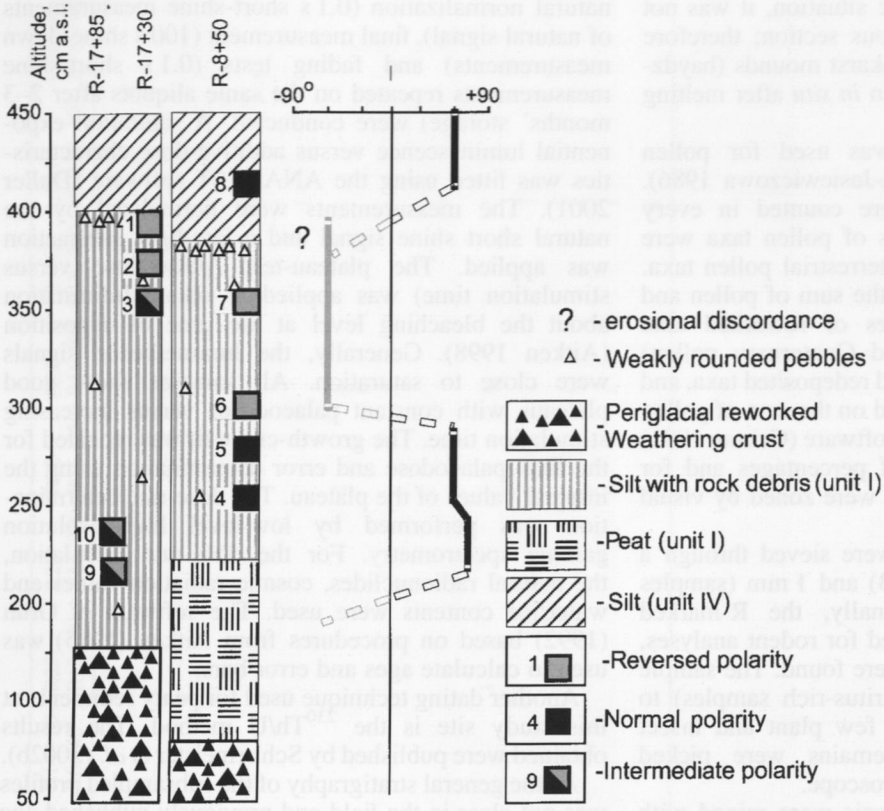

Fig. 4. Palaeomagnetic characteristics of sections R17+30, R17+85 and R8+50.

reconstruction approaches is discussed in Andreev *et al.* (2003b). In the present study, the same reference data sets and calculation techniques as described in Andreev *et al.* (2003a, b, 2004) were used. Mean July temperature and the annual sum of mean-day temperatures above 5°C (GDD5) have the most definitive effect on Arctic vegetation (Kaplan 2001) and are reconstructed from surface pollen spectra from the Russian Arctic with the highest confidence (Andreev *et al.* 2003a, b).

Results

Section R17

The 570-cm R17 section largely consists of old Ice Complex silty to sandy deposits with some smaller pebbles and peat inclusions covered by loess-like silty deposits (Fig. 3). The sample from the periglacially reworked Palaeogene weathering crust (80 cm a.s.l.) contains no pollen. Pollen spectra from deposits above can be divided into three pollen zones (Fig. 3). PZ-I consists of one sample from 160 cm a.s.l. and is notable for its low pollen concentration (5000 grains per cm^3) and large amounts of reworked Pinaceae. The spectrum is dominated by Poaceae and Cyperaceae with some other herb pollen (Caryophyllaceae, Cichoriaceae, *Artemisia*). PZ-II (*c.* 170–640 cm a.s.l.) is characterized by significantly higher pollen concentration (up to 35 000 grains per cm^3) and very low presence of reworked Pinaceae pollen. PZ-III (*c.* 640–670 cm a.s.l.) is similar to PZ-I.

The sample R17-R4 (420 cm a.s.l.) from a nearby-situated (less than 5 m) subsection contains few beetle remains, mostly mesic tundra species and species from typical and arctic tundra habitats (Table 3). There is only one typical tundra-steppe species, *Morychus viridis*, a habitant of the so-called sedge heaths (xerophilous *Carex argunensis* and *Polytrichum piliferum* dominated associations). Sediments from 450–480 cm a.s.l. (sample R17-B2) are richer in insect remains. The beetle fauna is dominated by mesic tundra species (52%) and species from typical and arctic tundra habitats (22%), but also includes habitants of dry tundra (12%). There are single remains of the meadow-steppe species, *Coniocleonus* sp. and the sedge-heath *Morychus viridis*. The sample R17-B1 (520 cm a.s.l.) contains only remains of one typical tundra species and one species from dry tundra habitat (Table 3). The sediments from another nearby-situated section, R17+30 (R3 from 320 cm and R2 from 360 cm a.s.l.) also contain species from dry, arctic, mesic tundra and sedge heaths habitats (Table 3).

Two IRSL dates, 134 ± 22 ka (Lya-2, 500 cm a.s.l.)

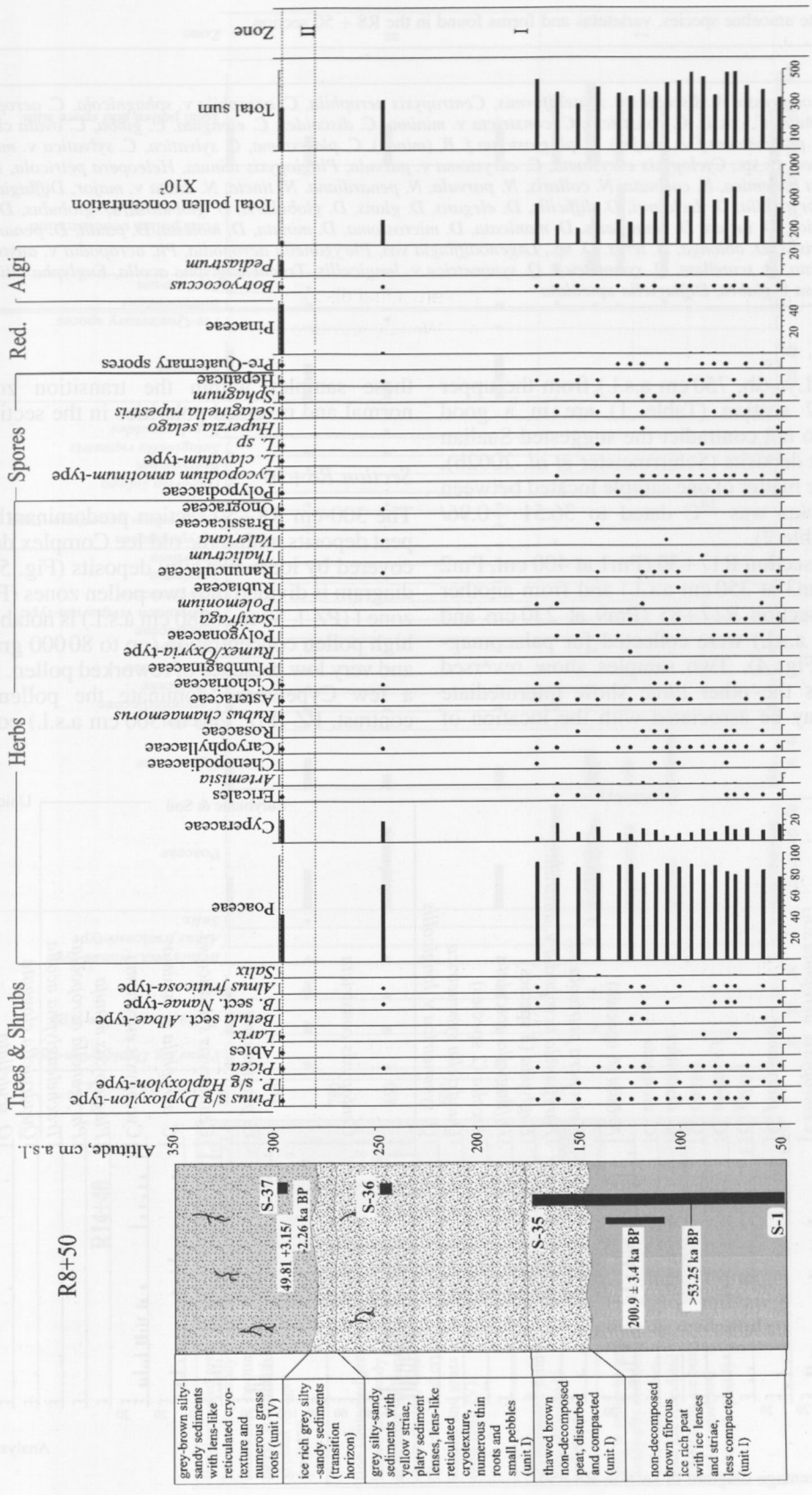

Fig. 5. Cryolithological structure and pollen percentage diagram of section R8+50 (for legend, see Fig. 3).

Table 4. List of testate amoebae species, varietetas and forms found in the R8 + 50 section.

Taxa name
Arcella arenaria v. *compressa, A. discoides* v. *scutelliformis, Centropyxis aerophila, C. aerophila* v. *sphagnicola, C. aerophila* v. *grandis, C. aerophila* v. *minuta, C. cassis, C. constricta, C. constricta* v. *minima, C. discoides, C. elongata, C. gibba, C. ovata* cf., *C. plagiostoma, C. plagiostoma f. A (major), C. plagiostoma f. B. (minor), C. platystoma, C. sylvatica, C. sylvatica* v. *microstoma, C. sylvatica* v. *minor, C.* sp., *Cyclopyxis eurystoma, C. eurystoma* v. *parvula, Plagiopyxis minuta, Heleopera petricola, H. petricola* v. *amethystea, Nebela bohemica, N. carinata, N. collaris, N. parvula, N. penardiana, N. tincta, N. tincta* v. *major, Difflugia ampululla, D. acuminata, D. bryophila, D. decloitrei, D. difficilis, D. elegans, D. glans, D. globularis, D. globulosa, D. globulus, D. lanceolata, D. leidy, D. limnetica, D. lucida, D. mamillaris, D. manicata, D. microstoma, D. minuta, D. molesta, D. paulii, D. penardi, D. petricola, D. pristis, D. oblonga, D. teres, D.* sp., *Lagenodifflugia vas, Phryganella acropodia, Ph. acropodia* v. *australica* cf., *Quadrulella elongata, Q. scutellata, Q. symmetrica, Q. symmetrica* v. *longicollis, Tracheleuglypha acolla, Euglypha ciliata f. glabra, E. laevis, E. strigosa* f. *glabra, Difflugiella apiculata*

and 77 ± 14 ka (Lya-3b, 750 cm a.s.l.) from the upper part of the R17 section (Table 1) are in a good agreement and do not contradict the suggested Saalian age of the lowest deposits (Schirrmeister *et al.* 2002b). However, organic matter of one sample located between both IRSL samples was ^{14}C dated to 36.51 +0.96/−0.86 ka BP (Table 2).

Samples from section R17+30 (Pm1 at 400 cm, Pm2 at 370 cm and Pm3 at 350 cm a.s.l.) and from another nearby-situated section R17+85 (Pm9 at 230 cm and Pm10 at 240 cm a.s.l.) were collected for palaeomagnetic analyses (Fig. 4). Two samples show reversed polarity, whereas the other three show intermediate values. These may be associated with the location of these samples within the transition zone between normal and reversed polarities in the section (Fig. 4).

Section R8+50

The 300-cm R8+50 section predominantly consists of peat deposits within the old Ice Complex deposits and is covered by loess-like silty deposits (Fig. 5). The pollen diagram is divided into two pollen zones (Fig. 5). Pollen zone I (PZ-I, 50 to *c.* 280 cm a.s.l.) is notable for its very high pollen concentration (up to 80 000 grains per cm^3) and very low presence of reworked pollen. Poaceae with a few Cyperaceae dominate the pollen spectra. In contrast, PZ-II (*c.* 280 to 300 cm a.s.l.) consists of one

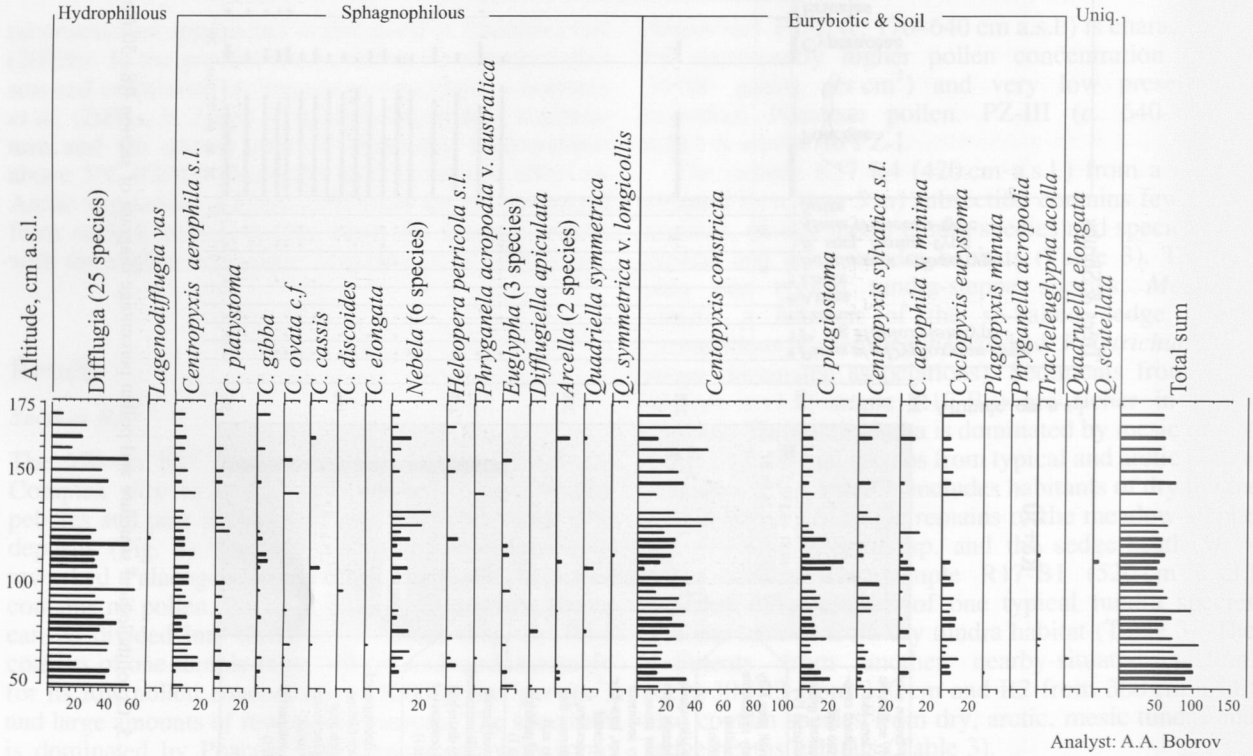

Fig. 6. Rhizopod percentage diagram of section R8+50.

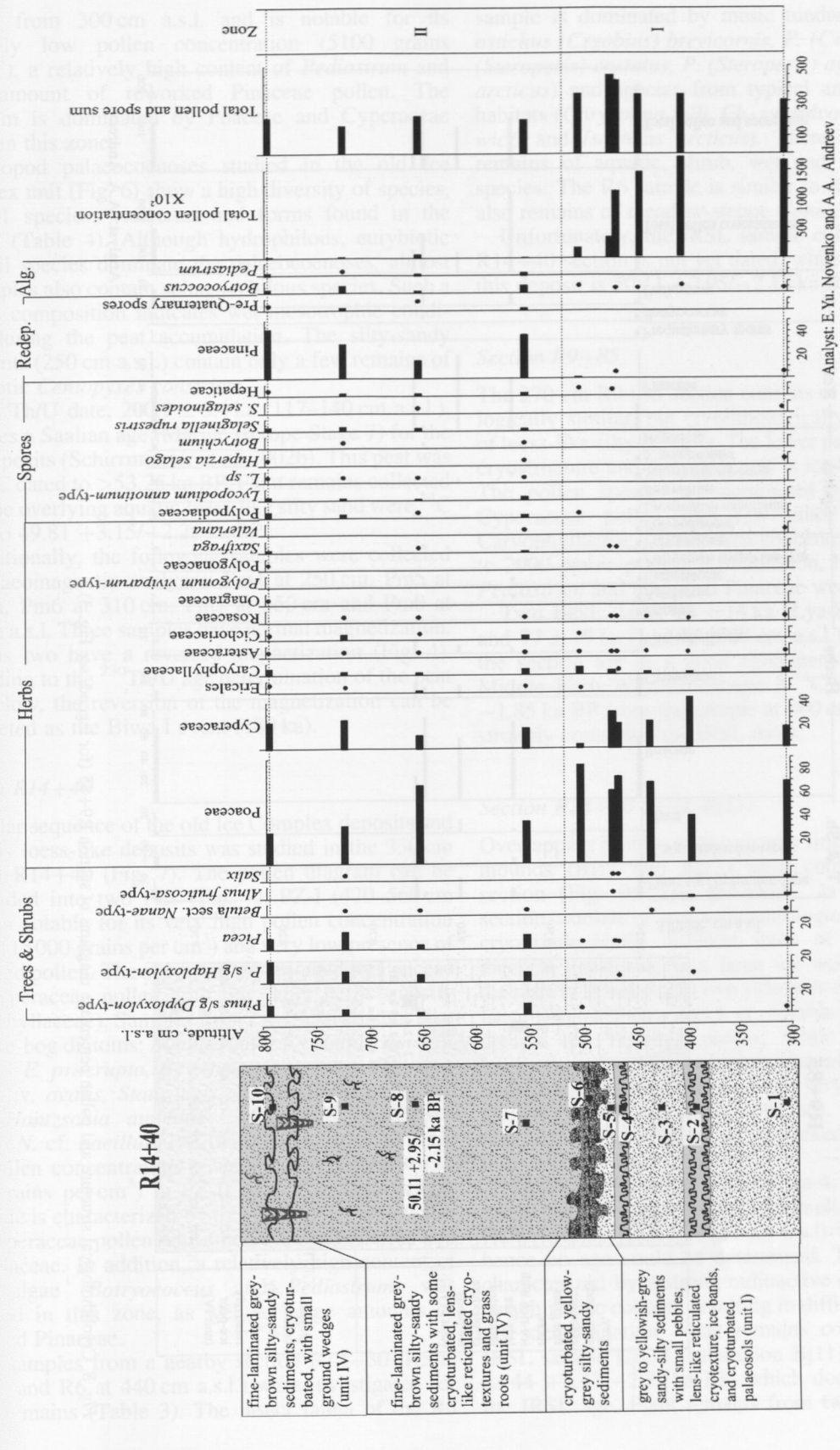

Fig. 7. Cryolithological structure and pollen percentage diagram of section R14+40 (for legend, see Fig. 3).

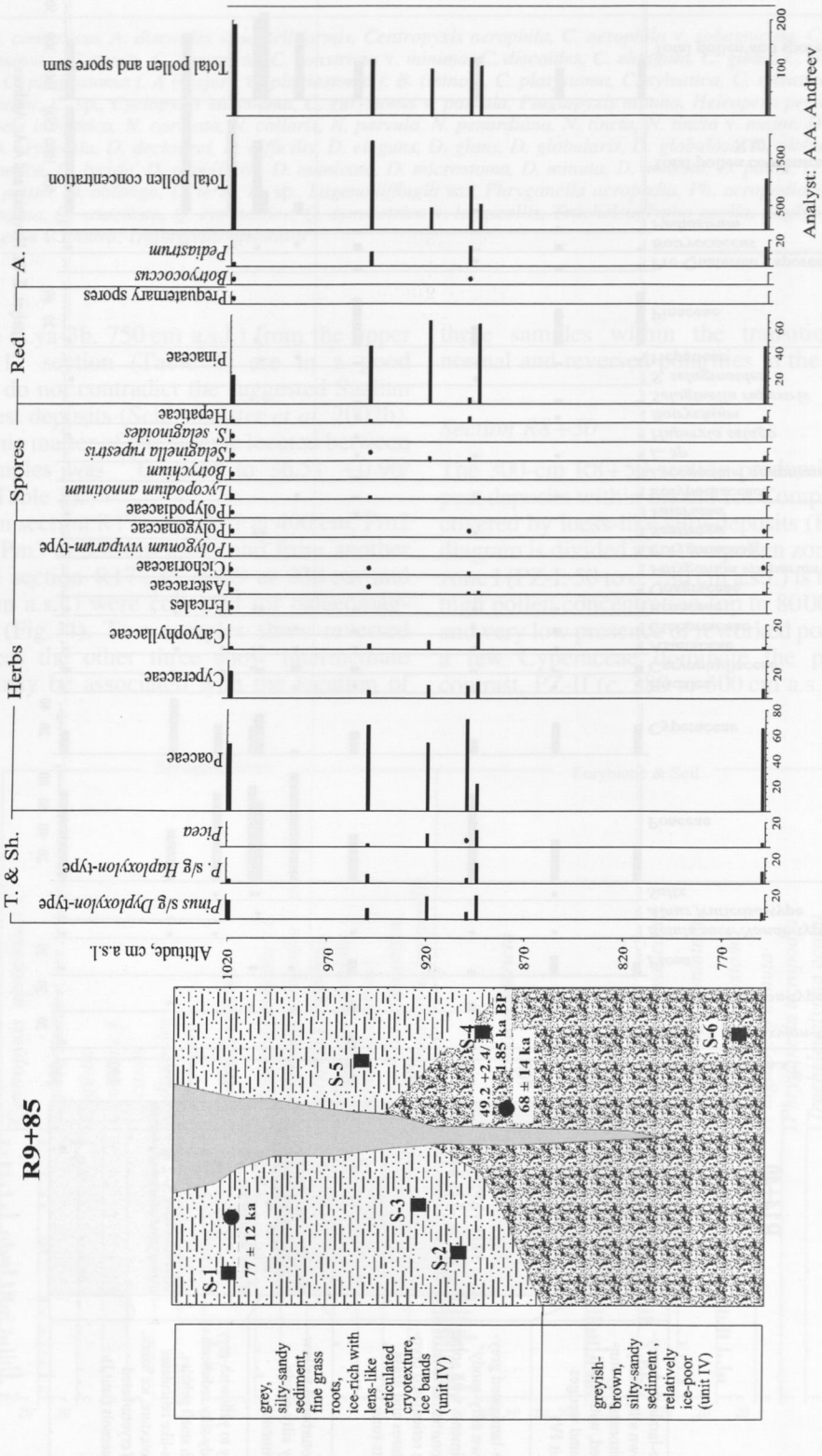

Fig. 8. Cryolithological structure and pollen percentage diagrams of section R9+85 (for legend, see Fig. 3).

sample from 300 cm a.s.l. and is notable for its relatively low pollen concentration (5100 grains per cm^3), a relatively high content of *Pediastrum* and large amount of reworked Pinaceae pollen. The spectrum is dominated by Poaceae and Cyperaceae pollen in this zone.

Rhizopod palaeocoenoses studied in the old Ice Complex unit (Fig. 6) show a high diversity of species, with 71 species, varietetas and forms found in the section (Table 4). Although hydrophilous, eurybiotic and soil species dominate the palaeocoenoses, almost all samples also contain sphagnophilous species. Such a species composition indicates wet mesotrophic conditions during the peat accumulation. The silty-sandy sediments (250 cm a.s.l.) contain only a few remains of eurybiotic *Centopyxes constricta*.

A ^{230}Th/U date, 200.9 ± 3.4 ka (117–140 cm a.s.l.), indicates a Saalian age (Marine Isotope Stage 7) for the peat deposits (Schirrmeister *et al.* 2002b). This peat was also ^{14}C dated to >53.25 ka BP. Plant remains collected from the overlying aquatic loess-like silty sand were ^{14}C dated to 49.81 +3.15/−2.26 ka BP.

Additionally, the following samples were collected for palaeomagnetic analyses: Pm4 at 250 cm, Pm5 at 280 cm, Pm6 at 310 cm, Pm7 at 350 cm and Pm8 at 420 cm a.s.l. Three samples have normal magnetization, whereas two have a reversed magnetization (Fig. 4). According to the ^{230}Th/U age determination of the peat lens below, the reversion of the magnetization can be interpreted as the Biwa I event (180 ka).

Section R14+40

A similar sequence of the old Ice Complex deposits and aqueous loess-like deposits was studied in the 330 cm section R14+40 (Fig. 7). The pollen diagram can be subdivided into two PZs (Fig. 7). PZ-I (470–560 cm a.s.l.) is notable for its very high pollen concentration (up to 115 000 grains per cm^3) and very low presence of reworked pollen. The spectra are dominated by Poaceae and Cyperaceae pollen with few other herbs (mostly Caryophyllaceae). Samples from PZ-1 also contain lake and lake-bog diatoms: *Eunotia lunaris* v. *subarcuata, E. gracilis, E. praerupta, E. exigua, E. suecica, Diatoma vulagre* v. *ovalis, Stauroneis anceps, Pinnularia borealis, Hantzschia amphioxys, Navicula pupula, N. mutica, N.* cf. *bacillum* (A. Bryantseva, pers. comm.). The pollen concentration is significantly lower (up to 7300 grains per cm^3) in PZ-II (*c.* 520–800 cm a.s.l.). The zone is characterized by the dominance of Poaceae and Cyperaceae pollen with some Caryophyllaceae and Cichoriaceae. In addition, a relatively high content of green algae (*Botryococcus* and *Pediastrum*) was observed in this zone, as well as large amounts of reworked Pinaceae.

The samples from a nearby section R14+30 (R5 at 400 cm and R6 at 440 cm a.s.l.) were investigated for insect remains (Table 3). The insect fauna of the R5 sample is dominated by mesic tundra species (*Pterostichus (Cryobius) brevicornis, P. (Cryobius)* spp., *P. (Steroperis) costatus, P. (Steroperis) agonus, Tachinus arcticus*) and species from typical and arctic tundra habitats (*Chrysolina tolli, Ch. subsulcata, Ch. wollosowiczi* and *Isochnus arcticus*). There are also a few remains of aquatic, shrub, wet and riparian habitat species. The R6 sample is similar to R5, but there are also remains of meadow-steppe *Coniocleonus* sp.

Unfortunately, the IRSL sample collected from the R14+40 section is not yet dated, while one ^{14}C age of this deposit is 50.11 +2.95/−2.15 ka BP.

Section R9+85

The 270-cm R9+85 section consists of two sedimentologically similar, but cryolithologically different parts of loess-like silty deposits. The lower part has a massive cryostructure and the upper part is ice-banded (Fig. 8). The pollen spectra are dominated by Poaceae and Cyperaceae pollen with few other herbs (mostly Caryophyllaceae). The pollen concentration is low (up to 2000 grains per cm^3). In addition, high amounts of *Pediastrum* and reworked Pinaceae were observed.

Two IRSL dates, 68 ± 14 ka (Lya-8, 880 cm a.s.l.) and 77 ± 19 ka (Lya-9, 1020 cm a.s.l.), obtained from the section are in a good agreement and point to a Middle–Early Weichselian age. A ^{14}C age of 49.2 +2.4/−1.85 ka BP from the sample at 900 cm a.s.l. does not strongly contradict the IRSL dates.

Section R18+50 (Bj11–Bj13)

Overlapping profiles of two closely situated thermokarst mounds (Bj11 and Bj13) were combined into one section (Fig. 9). The sediments, as in the R9+85 section, consist of two sedimentologically similar, but cryolithologically different units of loess-like silty deposits separated by a large ice wedge. The pollen diagram is divided into two subzones (Fig. 9). The PZ-Ia (1190–1375 cm a.s.l.) is notable for the higher content of Poaceae pollen, while PZ-Ib (1375–1430 cm a.s.l.) contains higher amounts of Cyperaceae pollen. The pollen concentration is very low (up to 2600 grains per cm^3) in both subzones. In addition, a relatively high content of reworked Pinaceae was observed in both subzones.

An IRSL date, 57 ± 10 ka (Lya-4, 1290 cm a.s.l.), shows the Zyryanian (Early Weichselian) age. Another IRSL sample (Lya-5, 1120 cm a.s.l) was not datable, hence no age could be determined. This sample was characterized by a strong radioactive disequilibria and very high ice content, resulting in difficulties with dose rate determination. Plant remains collected near the IRSL sample Lya-4 (subsection Bj11) were ^{14}C dated to 44 +3.43/−2.39 ka BP, which does not contradict the IRSL age. Plant remains from two other samples

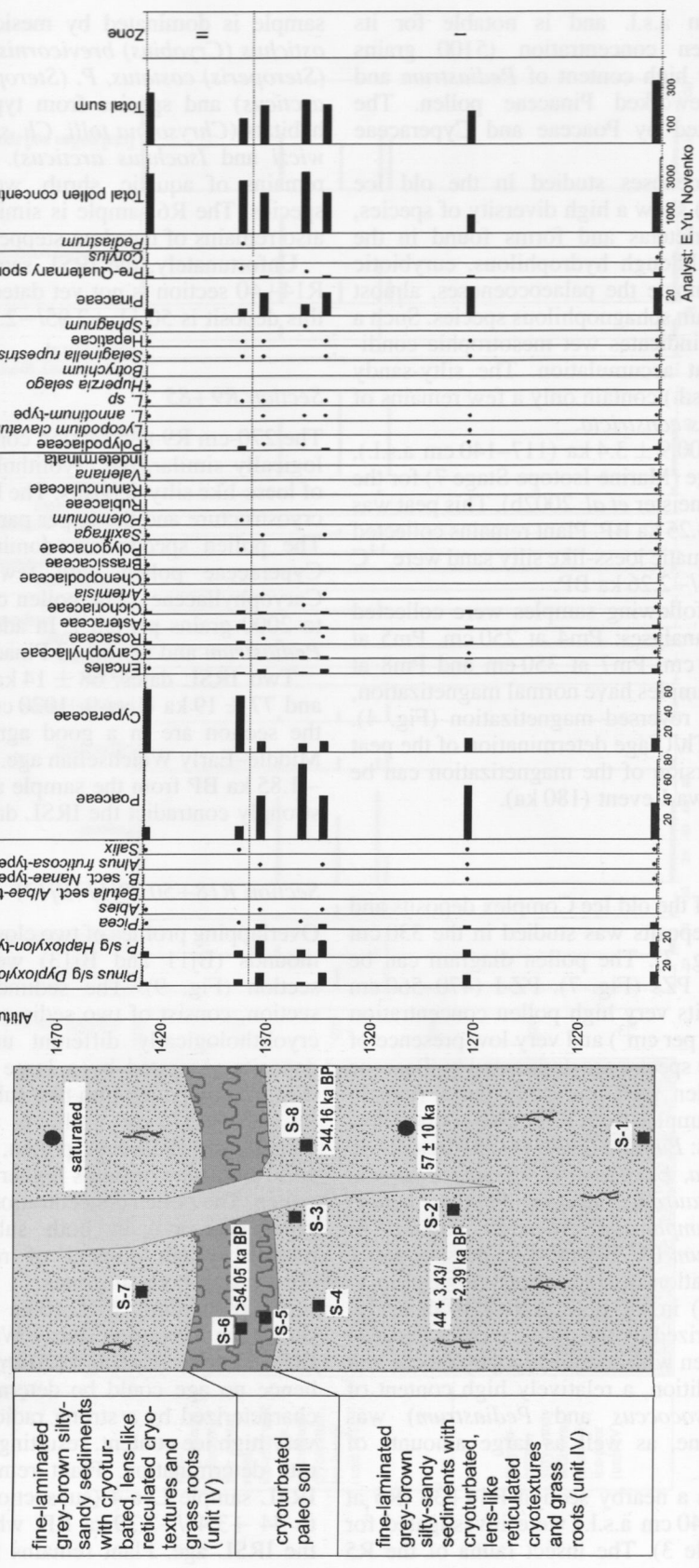

Fig. 9. Cryolithological structure and pollen percentage diagrams of section R18+50 (for legend, see Fig. 3).

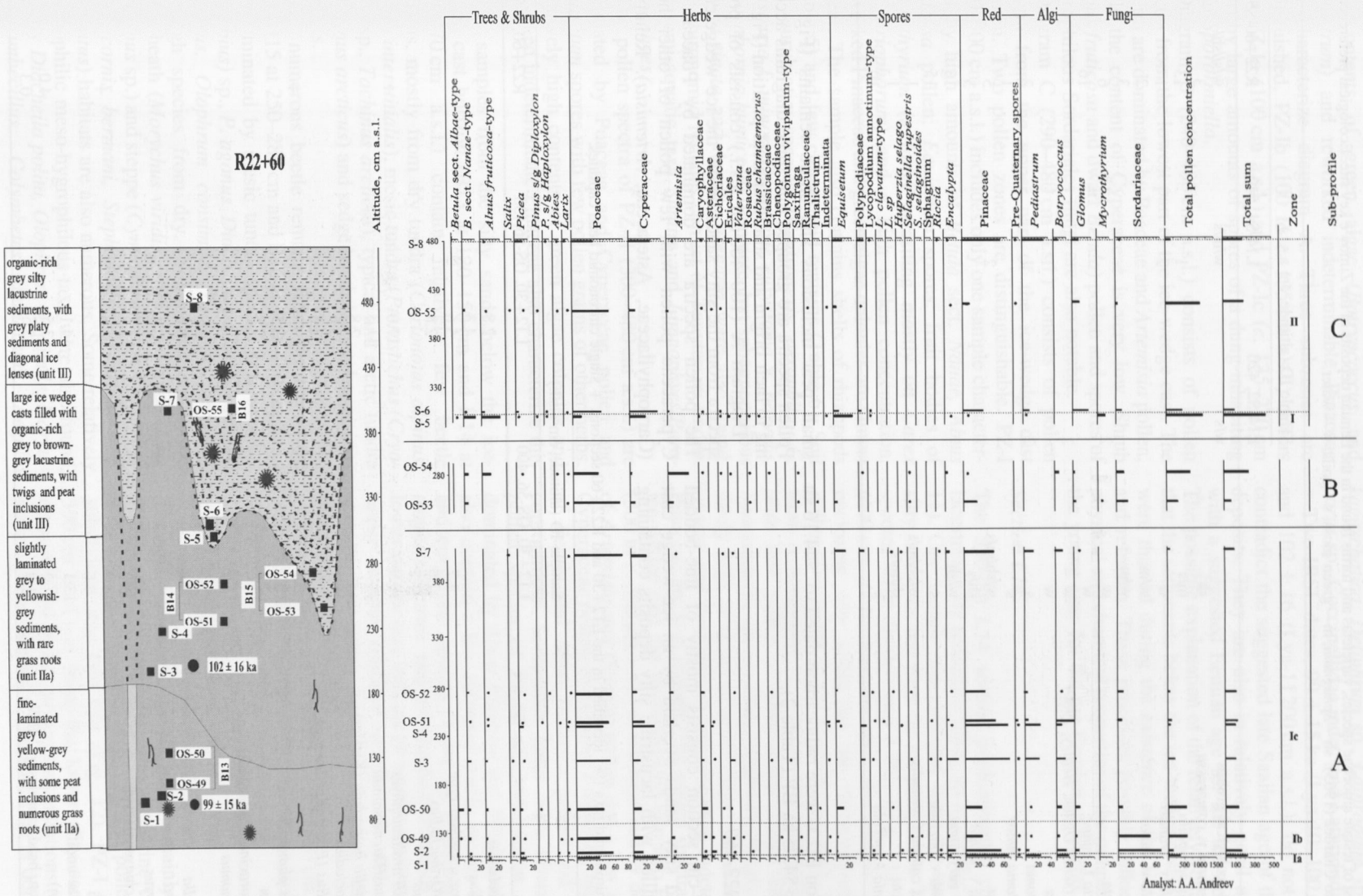

Fig. 10. Cryolithological structure and pollen percentage diagrams of section R22+60 (for legend, see Fig. 3).

Table 5. List of testate amoebae species, varietetas and forms found in the Eemian deposits of the Zimov'e key site. Ecological preferences are according to Chardez (1965): sh – *Sphagnum*, m – green moss, s – soils, w – water.

Species		Sample ID (altitude, cm a.s.l.)		
		L14-S2, 420	L14-S4, 540	R22+60-S5, 300
Dominated ecological groups		w/s	w/m/s	w/s//sh/
Arcella arenaria v. *compressa*	sh			3
Centropyxis aerophila	m/s		1	13
C. aerophila v. *grandis*	w		2	1
C. aerophila v. *minor*	w/m			2
C. cassis	w/m			3
C. constricta	w	2		6
C. constricta f. *minor*	w			16
C. ecornis (sensu Ogden, Hedley, 1980)	w	2		
C. elongata	w		1	
C. plagiostoma	s	2	1	2
C. plagiostoma minor	s			1
C. sylvatica	w/sh/m/s		2	5
C. sylvatica v. *minor*	sh/s			3
Cyclopyxis eurystoma	w/sh			16
C. eurystoma v. *parvula*	s			15
Plagiopyxis callida f. *grandis*	w/sh/m/s			1
Nebela tincta	sh/m/s			1
Schoenbornia humicola	s			10

(subsection Bj13) were radiocarbon dated to >44.16 ka BP and >54.05 ka BP (Table 2).

Section R22+60

The 400-cm section consists mostly of fine-bedded sands and silty sands overlaid by an ice-wedge cast horizon filled with lacustrine silty deposits containing small peat inclusions and shrub remains (Fig. 10). Pollen spectra are grouped into three diagrams according to their origin and stratigraphical position (Fig. 10).

Diagram A (100–400 cm a.s.l.) consists of pollen spectra from the silty sands below the ice-wedge casts. The pollen spectra are dominated by Poaceae and Cyperaceae pollen with few pollen of other herbs (Caryophyllaceae, Asteraceae, *Artemisia*). Relatively

Table 6. Chironomid taxa (%) identified in the L12+30 and R22+60 sections. + single chironomid head capsules.

Taxa	Sample ID (altitude, cm a.s.l.)		
	L12+30, OS-56, 400	L12+30, OS-56,430	R22+60, S-5,300
Bryophaenocladius		2.8	
Chaetocladius		4.3	
Corynoneura scutellata-type	1.7	5.6	
Cricotopus/Orthocladius	2.6	2.8	
Hydrobaenus	1.7		
Limnophyes/Paralimnophyes	13.9	17.0	+
Metriocnemus/Thienemannia		11.3	
Parakiefferiella bathophila (Kieffer)		2.8	
Paraphaenocladius	6.1	5.6	
Psectrocladius (P.) sordidellus-type	0.9	2.8	
Smittia	5.2		+
Chironomus plumosus-type	12.2	8.5	
Polypedilum	1.7	2.8	
Sergentia coracina (Zetterstedt)	1.7		
Stictochironomus	3.5		
Zavrelia	3.5	2.8	
Stempellinella	2.6	5.6	
Micropsectra	3.5		
Paratanytarsus		2.8	
Tanytarsus chinyensis-type	5.2	2.8	
Tanytarsini	13.9	5.6	+
Pentaneurini	7.0		
Chironomidae undiff.	13.1	14.1	
Total sum (*n*)	57.5	53.5	4.0
Concentration, head capsules g^{-1} DW	31.9	5.5	0.3

high contents of green algae (*Botryococcus* and *Pediastrum*) and reworked indeterminable Pinaceae also characterize diagram A. Three subzones are distinguished, PZ-Ib (100 to *c.* 135 cm a.s.l.) differs from PZ-Ia (100 cm a.s.l.) and PZ-Ic (*c.* 135–270 cm a.s.l.) by large amounts of spores of a dung-inhabiting fungi *Sporormiella*.

Diagram B (240–400 cm a.s.l.) consists of pollen spectra from the lowest part of the ice-wedge cast. The spectra are dominated by Poaceae and *Artemisia* pollen, while the content of Cyperaceae is very low. Shrub (*Alnus fruticosa* and dwarf *Betula*) pollen and spores of coprophilous Sordariales fungi are also notable.

Diagram C (290–480 cm a.s.l.) consists of pollen spectra from the upper part of the ice-wedge cast horizon. Two pollen zones are distinguishable. PZ-I (290–300 cm a.s.l.) includes only one sample characterized by high amounts of *Betula* sect. *Nanae, Alnus fruticosa* pollen; *Equisetum* spores, fruit bodies of *Mycrothyrium* (a fungi parasiting mostly on *Carex* and *Eriophorum*) and a high pollen concentration. Reworked Pinaceae and green algae colonies are almost absent. The sample also contains shells of rhizopods (Table 5) and few chironomid remains (Table 6). Soil and eurybiotic species (*Centropyxis aerophila, C. constricta f. minor, Cyclopyxis eurystoma* v. *parvula, Schoenbornia humicola*) dominate, but sphagnophilous *Nebela tincta* and *Arcella arenaria* were also found. The chironomid remains consist of Tanytarsini undiff. and semi-aquatic taxa *Smittia* and *Limnophyes/Paralimnophyes*.

The pollen spectra of PZ-II (300–480 cm a.s.l.) are dominated by Poaceae and Cyperaceae pollen and *Equisetum* spores with few pollen grains of other herbs. Relatively high contents of green algae colonies and reworked indeterminate Pinaceae also characterize this zone.

The samples from the silty sands below the ice-wedge cast horizon (B13 at 120–150 cm and B14 at 240–270 cm a.s.l.) contain relatively few beetle remains, mostly from dry tundra (*Curtonotus alpinus, Amara interstitialis*), mesic tundra (*Pterostichus (Cryobius)* sp., *Tachinus arcticus*), typical and arctic tundra (*Isochnus arcticus*) and sedge heath (*Morychus viridis*) habitats.

The numerous beetle remains from the ice-wedge cast (B15 at 250–280 cm and B16 at 400–430 cm a.s.l.) are dominated by mesic tundra species (*Pterostichus (Cryobius)* sp., *P. agonus, Diacheila polita, Cholevinus sibiricus, Olophrum consimile, Tachinus arcticus*), although species from dry (*Notiophilus aquaticus*), sedge heath (*Morychus viridis*), meadow-steppe (*Coniocleonus* sp.) and steppe (*Cymindis arctica, Chrysolina brunnicornis bermani, Stephanocleonus eruditus, S. fossulatus*) habitats are also numerous. Some relatively thermophilic meso-hygrophilous taxa were also found, namely *Diacheila polita, Olophrum consimile, Dorytomus imbecillus, Colymbetes dolabratus, Aegalia kamtschatica, Deliphrum* sp., *Lathrobium* sp., *Tachyporus* sp., Coccinellidae indet. and Lathridiidae indet.

Two IRSL dates, 99 ± 15 ka (Lya-10, 100 cm a.s.l.) and 102 ± 16 (Lya-11 200 cm a.s.l.), do not strongly contradict the suggested late Saalian age of the lowest deposits. They are also in relatively good agreement with a suggested Eemian age for the ice-wedge cast. The possible explanation of the relatively young ages is that the sediments below the ice-wedge casts (taberites) were thawed during the existence of the Eemian lake and refrozen. These processes possibly influenced the physical and chemical properties of the samples causing the young ages for the pre-Eemian sediments.

Section L14

The 350-cm L14 section predominantly consists of lacustrine silty sediments filling an ice-wedge cast (Fig. 11). One sample was collected from the surrounding silty sands, the rest from the ice-wedge cast. The pollen spectra were divided into 3 PZs (Fig. 11). The PZ-I (400 cm a.s.l.) includes only the sample from the enclosing silty sands that are characterized by low pollen concentration (2300 grains per cm^3). The spectrum is dominated by Poaceae and Cyperaceae pollen with few pollen of other herbs. Large amounts of *Sporormiella* spores (dung-inhabiting fungi) and relatively high contents of green algae colonies (*Botryococcus* and *Pediastrum*) and reworked indeterminable Pinaceae are also present. The pollen spectra from the ice-wedge cast can be subdivided into two PZs. PZ-II (300 to *c.* 360 cm a.s.l.) is distinguished by domination of *Artemisia* and Poaceae pollen and a low content of Cyperaceae pollen. In addition, a relatively high amount of *Betula* and *Alnus fruticosa* pollen and spores of coprophilous Sordariales fungi were observed. The pollen spectra of PZ-III (*c.* 360–540 cm a.s.l.) are dominated by *Alnus fruticosa* and *Betula* pollen. They also contain a few rhizopod shells, mostly from soils and eurybiotic species (Table 5). Hydrophilous *Centropyxis ecornis* and unidentified ostracods from the lower sample may indicate an aquatic environment. The upper sample contains mostly soil and eurybiotic species, but moss and soil habitant, *Centropyxis elongata*, is also present.

Two ^{14}C ages of > 50 420 yr BP (420 cm a.s.l.) and >50 880 yr BP (540 cm a.s.l.) confirm pre-Holocene age of the sediments.

Section L12+30

The 430-cm L12+30 section consists mainly of an ice-wedge cast horizon filled with lacustrine clayey silt, underlain by silty sands (Fig. 12). The pollen diagram subdivided into two PZs (Fig. 12). PZ-I (350 to *c.* 390 cm a.s.l.) is from the lower silty sands and is characterized by low pollen concentrations (up to 1200 pollen grains per cm^3). The spectrum is dominated by

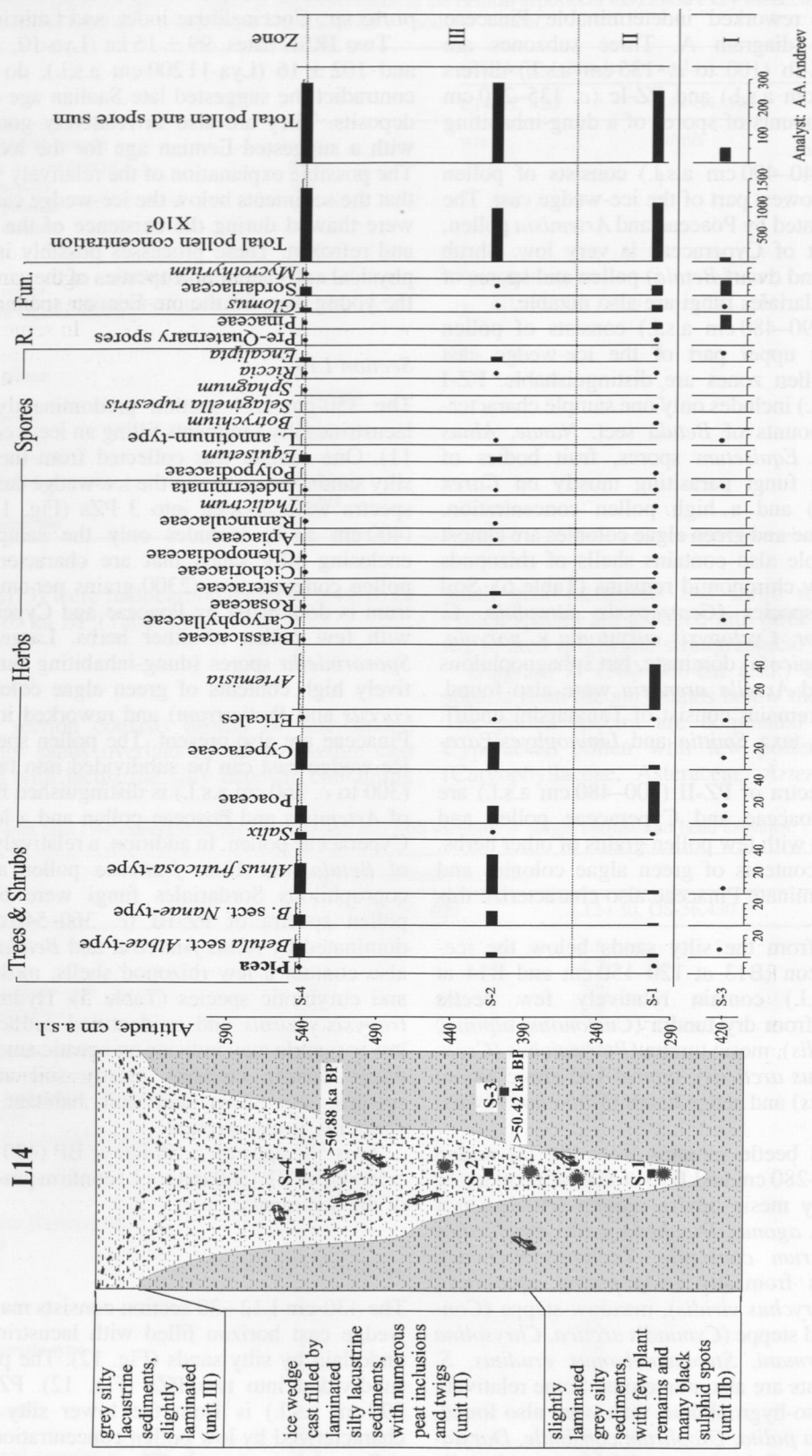

Fig. 11. Cryolithological structure and pollen percentage diagram of section L14 (for legend, see Fig. 3).

Poaceae and Cyperaceae pollen with few pollen of other herbs. Large amounts of *Sporormiella* spores from dung-inhabiting Sordariales fungi and relatively high contents of green algae colonies (*Botryococcus* and *Pediastrum*) and reworked indeterminable Pinaceae are also characteristic for the spectrum. The pollen spectra from the ice-wedge cast can also be subdivided into two subzones. The pollen spectra are dominated by *Alnus fruticosa* and *Betula* pollen with a rather high pollen concentration (5100–14600 grains per cm^3) in both subzones. The lower subzone (*c.* 390–550 cm a.s.l.) is notable for a higher content of *Salix*, while the upper subzone displays a higher content of *Artemisia* and Poaceae.

The sample from 400 cm a.s.l. contained numerous caddis fly (Trichoptera) remains and chironomid head capsules (Table 6). The sample from 430 cm a.s.l. contained only few caddis fly remains and concentration of chironomids is significantly lower. In both samples the chironomid head capsules are well preserved and identified to 22 taxonomic groups (Table 6). The assemblages are characterized by a high percentage (25–41%) of semi-aquatic *Smittia, Limnophyes/Paralimnophyes, Chaetocladius, Bryophaenocladius, Paraphaenocladius* and *Metriocnemus/Thienemannia* associated with moss habitats. The littoral thermophilous taxa (*Cricotopus/Orthocladius, Zavrelia, Psectrocladius sordidellus*-type, *Tanytarsus chinyensis*-type, *Stempellinella, Polypedilum, Corynoneura, Hydrobaenus*, Pentaneurini) associated with aquatic macrophytes are also numerous (25–27%). The thermophilous taxon, *Chironomus plumosus*-type dominates (8–12%) in the sublittoral/profundal group. Only a few indeterminable chironomid remains have been found in the sample from 700 cm a.s.l.

The deposits below the ice-wedge casts (B18 at 350–380 cm a.s.l.) contain a few beetle remains from different habitats (Table 3). The lacustrine silts (B17 at 400–430 cm and B19 at 700–730 cm a.s.l.) contain numerous beetle remains, mostly mesic tundra species (up to 45%), but species from dry tundra (up to 19%) and steppe (including sedge heath habitats) are also numerous. Typical riparian and aquatic species are common (up to 10% and 8%, respectively) as well. Some relatively thermophilic species, such as *Pelophila borealis* and *Olophrum consimile*, have also been found.

Discussion: palaeoenvironmental reconstructions

The most important result of this study is the clear evidence of humid and warm (interglacial) palaeoenvironmental conditions during an interval significantly older than the Holocene. This interval is most likely the Kazantsevo (Eemian) stage. Most of the age determinations, as well as the palaeoecological studies of the surrounding deposits, support this interpretation. The palaeoecological evidences of interglacial conditions were found in ice-wedge casts and lacustrine deposits (unit III). Organic remains in the ice-wedge casts were ^{14}C dated to minimal ages. The loess-like flood-plain deposits of units IIa and IV enclose the Eemian lake deposits of unit III.

Sediments of unit IIa were IRSL dated to 102 ± 16 and 99 ± 15 ka (Table 1). The deposits of unit IV were IRSL dated between 77 ± 14 and 57 ± 10 ka. There are also ^{14}C dates from unit IV with ages younger than the IRSL dates from the same unit, but there are also dates with minimal ^{14}C ages (Table 2). In some profiles from the central part of the outcrop, a disturbed horizon above unit I is noticeable. In the R17 profile it was IRSL dated to 134 ± 22 ka. This horizon is probably a sign of local hiatuses between unit I and unit IV, indicating the patch-like sedimentation during the Eemian. In general, units II and IV strongly differ from the Ice Complex of unit V in their facies properties.

Based on the radiocarbon ages, Meyer *et al.* (2002b) suggested that the loess-like flood-plain deposits rapidly accumulated at around 50 ka BP. It was assumed that there is a sedimentation hiatus of about 150 ka between unit I and the flood-plain deposits. The new IRSL ages clearly show that the postulated hiatus occurred locally and was much shorter in duration. In contrast to the Bykovsky Peninsula outcrops (Schirrmeister *et al.* 2002a; Meyer *et al.* 2002a; Andreev *et al.* 2002a; Bobrov *et al.* 2004), where a continuous sequence of one depositional unit (Late Pleistocene Ice Complex) is preserved, the studied outcrops on Bol'shoy Lyakhovsky Island represent a discontinuously formed sequence of permafrost deposits covering a much longer time period.

TL ages of unit I and II obtained by Arkhangelov *et al.* (1996) and Arkhangelov (pers. comm.) are certainly over the limit of the TL method for sediments of this kind (Table 7). On the contrary, the TL ages from unit II (Kunitsky *et al.* 2000) and from units III and IV (A. A. Arkhangelov, pers. comm.) fit quite well within the age range of interest in this paper. Insufficient bleaching of the sediments during accumulation is a major problem for thermoluminescence age determinations, and hence can cause geochronological confusion. This may quite certainly be excluded for the IRSL dating, as bleaching of the measured signal is faster and more effective. The plateau tests carried out on these samples indicate sufficient bleaching. Thus, it is assumed that the resetting of the IRSL signal of these deposits was complete during the transport and accumulation process.

Facies development

Geochronological studies of deposits older than the range of the radiocarbon method are still in progress,

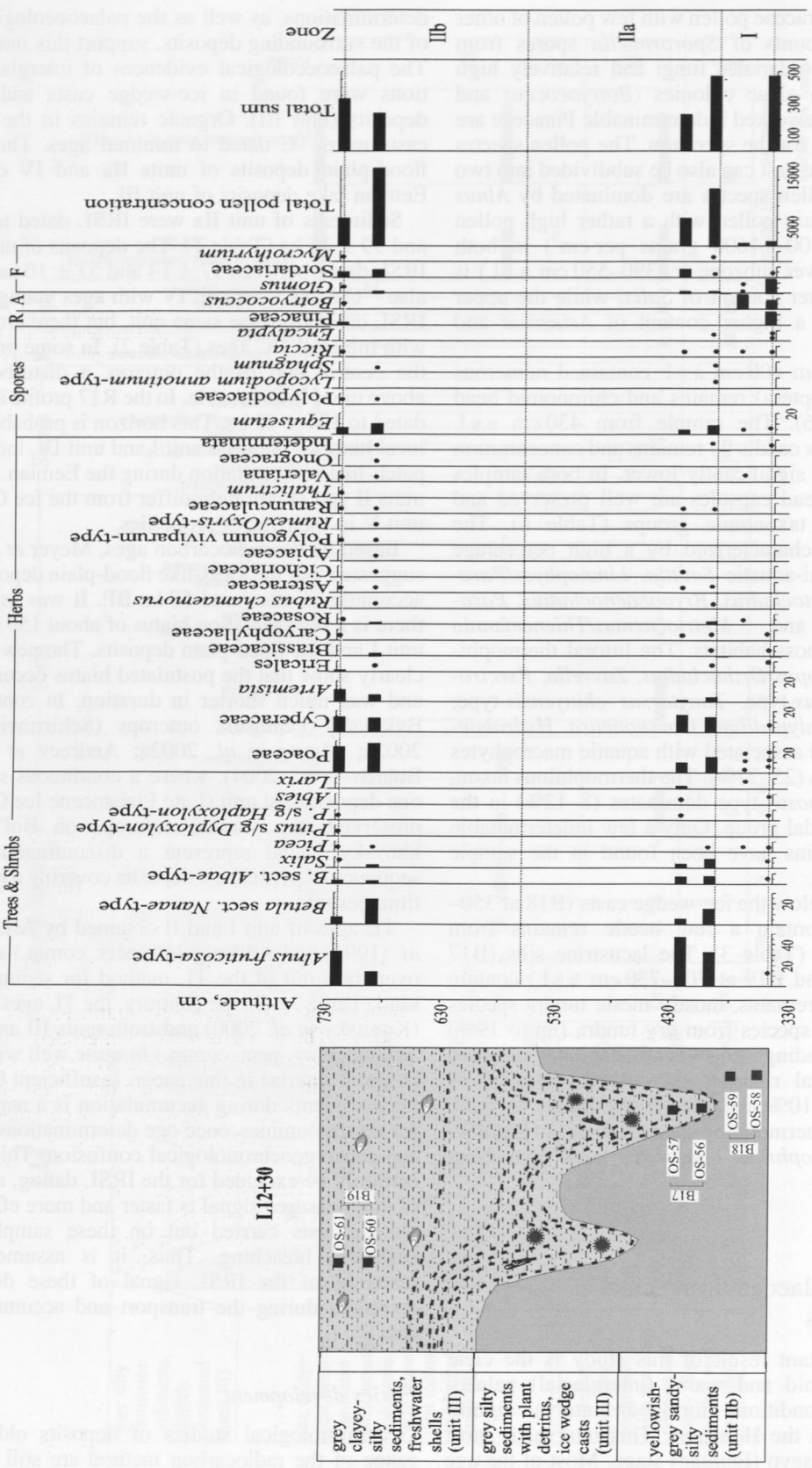

Fig. 12. Cryolithological structure and pollen percentage diagram of section L12+30 (for legend, see Fig. 3).

Table 7. Thermoluminescence ages from previous studies on the Bol'shoy Lyakhovsky Island.

Lab. no.	Unit, profile (altitude a.s.l., m)	Age (ka)	Source
RTL-821	Unit II, R16+70, 1.7	35 ± 10	Kunitsky (1998)
RTL-822	Unit II, R17+70, 2	36 ± 10	Kunitsky (1998)
RTL-741	Unit IIb, L9, 4.1	61 ± 15	Kunitsky (1998)
RTL-740	Unit IIb, R23+40, 5	96 ± 26	Kunitsky *et al.* (2000)
RTL-742	Unit II, R23+40, 2	114 ± 28	Kunitsky *et al.* (2000)
RTL-755	upper Unit IV, R04+10, 25	57 ± 15	Arkhangelov (pers. comm. 1998)
RTL-757	lower Unit IV, R07, 6.6	110 ± 28	Arkhangelov (pers. comm. 1998)
RTL-758	lower Unit IV, R07?	113 ± 28	Arkhangelov (pers. comm. 1998)
RTL-753	lower Unit IV, R11+70, 16	122 ± 30	Arkhangelov (pers. comm. 1998)
RTL-756	Unit III, R8, 12	136 ± 30	Arkhangelov (pers. comm. 1998)
RTL-754	Unit II, R7+10, 8	360 ± 90	Arkhangelov *et al.* (1996)
RTL-750	Unit I, R7+60, 2–2.5	950 ± 250	Arkhangelov *et al.* (1996)
RTL-751	Unit I, R7+60, 4.5	951 ± 240	Arkhangelov (pers. comm. 1998)
RTL-752	Unit I, R7+60, 1–1.5	980 ± 250	Arkhangelov *et al.* (1996)

especially for permafrost deposits. Therefore, difficulties with age determinations cannot be excluded. The ^{14}C ages presented in Table 2 reflect the Late Pleistocene (non-Holocene) age of the studied deposits. Based on ^{14}C ages of around 50 ka BP obtained from grass roots from the aquatic loess-like deposits (unit IV), it is proposed that during the Early Weichselian sedimentological facies developed similar to the pre-Eemian one. There are, however, no simple explanations for the younger ^{14}C ages. Possibly, they were caused by contamination during cryoturbation and thermokarst processes.

In general, a complex differentiation of the permafrost facies during the different stages of palaeolandscape development is suggested. This results in the coexistence of older and younger units (sedimentary bodies) at the same altitudes, or even the presence of older deposits at higher levels than younger sediments nearby. The suggested reasons are local erosion and further accumulation by thermokarst and thermoerosion as well as by fluvial processes. Observations of modern permafrost landscapes in the area indicate that relief strongly varies within short distances. Various periglacial forms (e.g. alas depressions, thermokarst lakes, thermoerosional valleys, small rivers and Ice Complex remains) coexist within a distance of a few hundred metres or less. A similar situation is postulated for the area during the Pleistocene, especially for the interstadial periods. During such periods, accumulation often takes place in depressions only, whereas on elevated areas erosion occurs or stable surfaces are formed. This pattern produces a patch-like sedimentation with local hiatuses. Additional factors causing a complicated geology are the strongly dislocated pre-Quaternary basement as well as neotectonic activities in the region. The proposed stages of landscape development in the area are presented below.

1. In the early Pleistocene, the basement was covered by a thick layer of so-called cryogenic elluvium (deposits of periglacially reworked Palaeogene weathering crust).
2. During the Middle Pleistocene (Saalian) the palaeorelief formed by basement structures was filled with old Ice Complex deposits (unit I), resulting in the formation of a relatively flat plain without strong geomorphological differences.
3. The overlying loess-like silty sands of unit II reflect a change of the facies. It is proposed that both subunits (a and b) were accumulated on a flood-plain with shallow lakes at the end of the Taz (Saalian) time. The local stratigraphical name of these deposits is the Kuchchugui Suite.
4. During the Eemian (Kazantsevo) stage, ice wedges of unit II were thawed due to thermokarst processes. The thermokarst depressions were subsequently filled with lacustrine deposits (unit III). Strong erosion processes took place during this stage. A frequently observed reworking horizon covering the ice wedges of the old Ice Complex unit reflects this erosion, which was probably caused by seismotectonical events provoking a reorganization of the runoff regime. The deposits were then eroded and redeposited in local depressions and valleys several times, resulting in the facies nesting described above.
5. Loess-like deposits of unit IV accumulated at the beginning of the Zyryanian (Early Weichselian) stage. These deposits are sedimentologically similar to the pre-Eemian unit IIa (they differ in their ice-banded cryostructure and the absence of peat inclusions) and they probably consist of reworked material from unit IIa.

The Saalian (Taz) environment

The age of the lowermost unit I is still indistinct. According to the $^{230}Th/U$ date from the R8+50 section, peat accumulated *c.* 200 ka BP. This age seems to be reliable, as frozen peat is a closed system for uranium

and thorium (Schirrmeister *et al.* 2002a). It is also in good agreement with the upper Middle Pleistocene age suggested by Romanovskii (1958b). On the contrary, the TL dates obtained by Arkhangelov from unit I (Table 7) are not reliable, since they are far beyond the TL dating range limit for these kinds of sediments. TL ages up to 300 ka are reliable only for polymineralic fine-grained samples (Zöller *et al.* 1988; Shingvi *et al.* 1989). Although TL ages up to 400 ka are possible for coarse-grained potassium feldspar samples, large errors occur for ages older than 120 ka (Mejdahl 1988; Huett & Jaeck 1989).

Palaeomagnetic investigations showed that samples from the lowermost unit I are reversal magnetized. Arkhangelov *et al.* (1996) believes that it is the Jaramillo reversal event in the early Pleistocene. However, according to the ^{230}Th/U date, it can be attributed to the Biwa I reversal event (*c.* 179–189 ka BP; Nowaczyk & Antonow 1997).

A middle Saalian stadial (?). – The oldest pollen spectrum from the studied deposits is PZ-I of R17 (Fig. 3), directly above the periglacially reworked remains of the weathering crust. It reflects sparse grass-sedge vegetation cover during this time. Relatively high contents of Asteraceae and Cichoriaceae, as well as large amounts of reworked pollen, indicate the presence of disturbed soils and erosion of older deposits. Therefore, the reflected severe interval can be assigned to a stadial during the middle Saalian time.

An interstadial c. 200–170(?) ka. – Pollen spectra from the PZ-II of R17 (Fig. 3), PZ-I of R8+50 (Fig. 5) and PZ-I of R14+40 (Fig. 7) sections indicate that dense grass-sedge tundra occupied the area after the severe stadial time reflected in the lowest part of section R17. Absence of typical cryoxerophitic taxa, high pollen concentrations and low amounts of redeposited pollen and spores indicate relatively warm and wet summers, probably similar to (or even warmer than) modern ones.

Rhizopod remains from the old Ice Complex deposits of section R8+50 (Fig. 6, Table 4) are numerous and reflect a high taxa diversity (71 species, varietetas and forms). The modern species diversity in the high Arctic is lower. For example, only 45 taxa are found in the modern habitats of Barents and Kara Seas coasts (Beyens *et al.* 2000). The relatively well-investigated rhizopod fauna of Spitzbergen consists of 48 taxa (Balik 1994). The high species diversity in the R8+50 section may reflect a climate more favourable for the rhizopods than today's climate on the island. The rather stable contents of palaeocoenoses in peat indicate a relatively stable hydrothermal regime during the peat accumulation. A find of rare *Quadrulella* species is particularly interesting. These species were previously not reported from the region. *Q. elongata* is found only in Belgium and Venezuela, while *Q. scutellata* was only reported from North America (Chardez 1967), hence their presence in the Saalian sediments shows that the distribution of these rare species was significantly different from today.

Generally, pollen spectra of unit I are similar to the pollen spectra from the upper part of the so-called Kuchchugui suite. They accumulated in the vicinity of the Laptev Sea coast during the end of the Middle Pleistocene, and at some southern localities before the last interglacial (e.g. Barkova 1970a, 1982). According to Barkova (1970a, 1990), treeless grass-dominated vegetation prevailed in the Laptev Sea region during late Kuchchugui time.

The beetle fauna of the old Ice Complex sediments (R17, R17+30 and R14+30 sections) is dominated by mesic tundra species and species from typical and arctic tundra habitats. The typical tundra-steppe beetles are almost absent in the sediments. Only a few remains of *Coniocleonus* sp. and *Morychus viridis*, which are common in Late Pleistocene deposits and occur in modern dry tundra habitats, were found (Kuzmina 2002).

Therefore, based on pollen, insect and rhizopod records, it is assumed that this interval during the middle Saalian time is an interstadial with relatively warm and wet summers compared to modern conditions. Tundra habitats ecologically similar to modern ones dominated the area. However, stable isotopes from the ice wedges sampled in section R17 suggest severe winter conditions during that time (Meyer *et al.* 2002b).

It is difficult to estimate the age of the interstadial. Taking into consideration the stratigraphical sequence, the IRSL and ^{230}U/Th dates and the comparison of the pollen records with the published late Kuchchugui ones, a Saalian age for the lowest stadial and interstadial sediments is assumed. Alternatively, according to Arkhangelov *et al.* (1996) and Sher *et al.* (2002), these sediments may have accumulated during the late Pliocene/early Pleistocene. To accept their point of view, it must be assumed that there is a continuous hiatus between these early Pleistocene sediments and the overlying Middle/Late Pleistocene sediments. This hiatus must be several hundreds of thousands of years long. However, the existence of such a hiatus requires evidence. It is likely that only palaeontological remains, if they can be found *in situ*, would help to determine the age of the sediment.

It is also difficult to estimate the duration of the interstadial, but if we take into consideration as an example the duration of the Karginsky (Middle Weichselian) interstadial in Northern Siberia (e.g. Isaeva 1984; Lozhkin 1987; Anderson & Lozhkin 2001; Andreev *et al.* 2002a, b), it may have lasted *c.* 30 ka and ended *c.* 170 ka BP or earlier. Gavrilov & Tumskoy (2001) also suggested that a relatively warm interval in northern Yakutia during the Middle Pleistocene ended about 170 (190) ka BP.

A late Saalian (Kuchchugui) stadial c. 170(?)–130 ka. – The pollen spectra from PZ-III of R17 (Fig. 3), PZ-

Table 8. Environmental changes in the region *c.* 200–100 ka BP.

Stratigraphy		Age, ka	Facies	Pollen	Insects	Rhizopods	Palaeoenvironment
Early Weichselian	Stadial (Zyryanian) Unit IV)	<120	flood plain	spectra similar to Unit IIa ones			grass-sedge dominated vegetation; disturbed soils and erosion, severe climate
Eemian	Interstadial (Kazantsevo, Krest-Yuryakh) Unit III	*c.* 130 -110	tundra plain with thermokarst depressions and lakes	grass-sedge dominated spectra with few shrub pollen, lower pollen concentration, larger amounts of reworked conifers	numerous mesic tundra taxa, but dry tundra and tundra-steppe species are also common, warm-adapted chironomids taxa		grass-sedge dominated vegetation severe climate
				shrub (alder, birch, and willow dominated spectra, high pollen concentration.		eurybiotic and soil taxa dominated; hydrophilous species are absent	shrub tundra, warm climate (summer temperatures 4-5°C higher them modern)
				grass and *Artemisia* dominated spectra, presence of *Alnus fruticosa*, *Salix*, *Betula nana* pollen			open grass and *Artemisia* dominated vegetation, rather warm climate resulting in melting of Saalian ice wedges
Late Saalian (Taz)	Stadial (Kuchchugui) Unit IIa+b	*c.* 170 -130	flood plain with shallow lakes	grass-sedge dominated spectra with some Caryophyllaceae, Asteraceae, and Cichoriaceae; rather high contents of green algae colonies, very low pollen concentration, large amounts of reworked conifers	rare insect remains, mostly from dry tundra		disturbed soils and erosion, sparse grass-sedge dominated vegetation, cold climate
	Interstadial Unit I	*c.* 200-170	polygonal tundra plain	grass dominated spectra with few sedges, high pollen concentration	mesic tundra, and typical and arctic tundra taxa	high species and forms diversity, soil climate more favourable than today	dense grass dominated tundra, rather warm and wet summer, but cold winter
	Stadial Unit I	prior to 200		grass-sedge dominated spectra with few Asteraceae and Cichoriaceae, low pollen concentration, large amounts of reworked conifers			sparse grass-sedge dominated vegetation, disturbed soils, severe climate

II of R8+50 (Fig. 5), PZ-II of R14+40 (Fig. 7), R9+85 (Fig. 8), R18+50 (Fig. 9), diagram A of the R22 section (Fig. 10), PZ-I of L14 (Fig. 11) and PZ-I of L12+30 (Fig. 12) reflect a dramatic deterioration of the environmental conditions compared with the previous interstadial ones. The lower pollen concentrations may reflect sparse grass-sedge vegetation cover during this time and/or a dramatic decrease of pollen production. Relatively high contents of Asteraceae and Cichoriaceae as well as large amounts of reworked pollen may mirror the presence of disturbed soils and the erosion of older deposits. The presence of green algae colonies (up to 15%) suggests that sedimentation obtained in shallow water conditions (probably, flood-plain environment). A large amount of the dung-inhabiting Sordariales fungi can be seen as an indication of grazing herds in the area during that time. The sediments contain only a few insect remains of species from dry, mesic, typical and arctic tundra habitats. The very low presence of insect remains is also evidence of the unfavourable environmental conditions and/or unfavourable conditions for insect preservation.

The reconstruction of an extremely cold climatic interval during the late Saalian (Kuchchugui), based on the palaeoecological data, is also supported by the isotopic analyses of the Kuchchugui ice wedges (Meyer *et al.* 2002b). It can be concluded that an interval with severe environmental conditions occurred at the end of the Middle Pleistocene.

As with the earlier interval, the duration of the stadial is difficult to determine. Considering the suggested duration of the interstadial described above, and the interglacial character of the pollen spectra from overlying ice-wedge casts, it is estimated that the stadial began *c.* 170 ka and ended *c.* 130 ka BP, shortly before the last interglacial.

A TL date obtained by Arkhangelov from Unit IIa of 360 ± 90 ka BP (Table 7) is not reliable when taking into consideration the dating limit of the TL method. On the contrary, a TL date of 136 ± 34 ka BP obtained from 'blue lacustrine sediments' (grey lacustrine sediments from unit III?) fits well with the suggested late Saalian age of the stadial and the Eemian (Kazantsevo) age of the interstadial.

The Eemian (Kazantsevo) c. 130–110 ka. – Pollen spectra from the diagram B of the R22 section (Fig. 10) and PZ-II of the L14 section (Fig. 11) reflect that open plant associations with Poaceae and *Artemisia* dominated vegetation at the beginning of the Eemian. The high content of *Artemisia* pollen in the spectra may indicate that disturbed and/or denuded soils were common in the area. Alternatively, the dominance of Poaceae and *Artemisia* in the spectra may indicate steppe vegetation, which would correlate well with the insect records. Although mesic tundra insects dominate in the early Eemian sediments (ice-wedge cast samples from R22 and L12+30 sections), the relatively high presence of dry tundra and steppe (tundra-steppe) species also indicates steppe or steppe-like habitats at the beginning of the Eemian. The rather numerous coprophilous Sordariales fungi spores may indicate the presence of grazing herds at this time. Relatively high contents of shrub (*Alnus fruticosa, Salix, Betula nana*) pollen probably reflect that shrubs started to grow in more protected places close to the site. The climate was rather warm, resulting in the melting of the late Saalian ice wedges.

High contents of *Alnus fruticosa, Betula* and Cyperaceae pollen and *Equisetum* spores are characteristic for the PZ-I of the diagram C of the R22 section (Fig. 10), PZ-II of the L14 section (Fig. 11) and of the L12+30 section (Fig. 12). The low content of Ericales pollen is characteristic for the Eemian sediments from the Zimov'e River key section in comparison with Holocene ones (Andreev 2002a, b, and unpublished data). This probably indicates a much drier environment during the Eemian than during the Holocene. The numerous remains of fossil *Alnus fruticosa* and *Betula nana s.l.* twigs and trunks are also characteristic for the middle Eemian deposits of the Zimov'e site. Species from mesic and dry tundra habitats dominated the beetle fauna. The studied interglacial deposits (Table 5) also contain eurybiotic and soil rhizopods (e.g. *Centropyxis aerophila, Cyclopyxis eurystoma* v. *parvula, Schoenbornia humicola*), as well as a few sphagnophilous ones (*Nebela tincta, Arcella arenaria* v. *compressa*), while hydrophilous species are absent. The species composition (dominance of *Centropyxis* species) indicates well-drained habitats with sufficient mineral nutrition. The polymorphic character of the species (many species are present not only by f. *typica*, but also subspecies, varieties and f. *minor*) reflects frequent changes of the hydrological regime in the area. For example, the presence of *Plagiopyxis callida* f. *grandis* and *Nebela tincta* together with numerous *minor* forms of *Centropyxis* species may indicate short-term dry conditions. Chironomid assemblages and caddis fly remains reflect environmental conditions of shallow lakes with a boggy catchment area around the studied sites. The lakes were likely characterized by an extensive development of aquatic macrophytes in littoral zone and floating moss mats along the lake shoreline. The high abundance of thermophilous taxa may indicate relatively high summer air temperatures during this time. Thus, environmental records show that shrub tundra with numerous lakes dominated the area during the Eemian optimum.

Unfortunately, the Eemian deposits on the Zimov'e River key site survived only within the few buried ice-wedge casts and only a few fragmented interglacial palaeoecological records were found, making the reconstruction of short-term environmental fluctuations during the interglacial more difficult. However, it can be concluded that according to pollen and beetle data, the steppe or tundra-steppe habitats were common in the area at the beginning of the interglacial. Shrub commu-

nities also grew in wetter places. Climate was warm and relatively dry. The palaeoenvironmental records suggest that shrub tundra dominated the area later, during the middle Eemian. The larger amounts of Poaceae, *Betula nana* and *Artemisia* pollen, as well as higher numbers of beetle remains from dry tundra and sedge heath habitats in the upper part of the L12+30 section, may indicate some climatic deterioration during the middle-late Eemian. The pollen spectra from PZ-II of diagram C of the R22 section contains large amounts of reworked Pinaceae pollen and few shrub pollen, reflecting a significant deterioration of climate at the beginning of the Eemian termination.

Thermal conditions reconstructed from pollen are consistent with the qualitative interpretation of the proxy records. The reconstructed July temperatures vary from 7.8 to 9.6°C (taking into account the −0.9°/+1.3°C errors of the reconstruction). Hence, the July temperatures were at least 4–5°C higher than today during the climate optimum of the Eemian. Reconstruction of the effective temperatures above 5°C also suggests that summers were warmer (GDD5 = 150–230°C) than today (GDD5 = 0°C) during the optimum. In the BIOME1 vegetation model (Prentice *et al.* 1992), the reconstructed GDD5 values correspond to the tundra vegetation. Temperature reconstruction from the pollen spectra attributed to the early and late Eemian suggests significantly colder (similar to present day) conditions in comparison to the climate optimum.

The last interglacial (Kazantsevo, Krest-Yuryakh) pollen records are relatively well known in northern Yakutia (e.g. Rybakova 1962; Barkova 1970b; Rybakova & Kolesnikov 1983; Pirumova & Rybakova 1984; Sher 1991; Lozhkin & Anderson 1995). Generally, such records contain high percentages of tree and shrub pollen, reflecting that forest or tundra-forest vegetation dominated the northern Yakutia. As already pointed out by Sher (1991), 'traditionally, it was thought that during "warm" stages, treeless tundra-steppe communities were replaced by forest-tundra or taiga communities'. However, such simple interpretations do not explain how Pleistocene grazing mammal populations and steppe insects survived during warm and wet stages (Sher 1991). The new environmental records show that dry steppe-like habitats existed during the Eemian in northern Yakutia, especially in early and late Eemian, but not during the Holocene. This may explain why Pleistocene mammoth fauna survived during the last interglacial but disappeared in the early Holocene.

Transition to Late Pleistocene stadial (Zyryanian, Early Weichselian). – According to the IRSL ages from the upper part of sections R17, R18+50, R9+85 and TL dates from Unit IV (Table 7), the loess-like silty sands have accumulated after the Eemian. Both sedimentological and palaeoenvironmental records reflect environmental conditions at the beginning of the Early Weichselian stadial similar to the late Saalian conditions.

Conclusions

The palaeoecological records from the Zimov'e site are the first IRSL and ^{230}Th/U dated records documenting the environmental history of the Laptev Sea region during the Taz (Late Saalian) and Kazantsevo (Eemian) (Table 8). Pollen spectra and beetle fauna suggest that wet grass-sedge tundra habitats dominated during the interstadial *c.* 200–170(?) ka ago. Summers were relatively warm and wet, while stable isotopes reflect severe winter conditions.

The pollen spectra reflect sparser grass-sedge vegetation cover during the stadial, *c.* 170(?)–130 ka ago. Environmental conditions were much more severe compared with the previous interstadial.

Open Poaceae and *Artemisia* plant associations dominated vegetation at the beginning of the Kazantsevo (Eemian). Some shrubs (*Alnus fruticosa, Salix, Betula nana*) grew in more protected and wetter places. Climate was fairly warm (similar to modern conditions) during this time, resulting in the partial melting of Taz (Saalian) ice wedges. Shrub tundra with *Alnus fruticosa* and *Betula nana s.l.* dominated the vegetation in the area during the middle Eemian climatic optimum, when summer temperatures were 4–5°C higher than today. The steppe-like habitats were rather widely distributed during the last interglacial, especially during early and late stages.

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